Towards New Comet Missions

Journal Item

Space Sci Rev (2019) 215:47
https://doi.org/10.1007/s11214-019-0611-0

Towards New Comet Missions

N. Thomas[1] · S. Ulamec[2] · E. Kührt[3] · V. Ciarletti[4] · B. Gundlach[5] · Z. Yoldi[1] · G. Schwehm[6] · C. Snodgrass[7,8] · S.F. Green[7]

Received: 10 April 2019 / Accepted: 25 September 2019

Abstract The Rosetta observations have greatly advanced our knowledge of the cometary nucleus and its immediate environment. However, constraints on the mission (both planned and unplanned), the only partially successful Philae lander, and other instrumental issues have inevitably resulted in open questions. Surprising results from the many successful Rosetta observations have also opened new questions, unimagined when Rosetta was first planned. We discuss these and introduce several mission concepts that might address these issues. It is apparent that a sample return mission as originally conceived in the 1980s during the genesis of Rosetta would provide many answers but it is arguable whether it is technically feasible even with today's technology and knowledge. Less ambitious mission concepts are described to address the suggested main outstanding scientific goals.

Comets: Post 67P / Churyumov-Gerasimenko Perspectives
Edited by Nicolas Thomas, Björn Davidsson, Laurent Jorda, Ekkehard Kührt, Raphael Marschall, Colin Snodgrass and Rafael Rodrigo

✉ N. Thomas
nicolas.thomas@space.unibe.ch

1 Physikalisches Institut, University of Bern, Sidlerstr. 5, 3012 Bern, Switzerland

2 Deutsches Zentrum für Luft- und Raumfahrt (DLR), RB-MUSC, Linder Höhe 1, 51147 Cologne, Germany

3 Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Asteroiden und Kometen, Rutherfordstraße 2, 12489 Berlin, Germany

4 LATMOS/IPSL, UVSQ (Université Paris-Saclay), UPMC (Sorbonne Univ.), CNRS, 11, boulevard D'Alembert, 78280 Guyancourt, France

5 Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany

6 ESA-ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

7 Planetary and Space Sciences, School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK

8 Institute for Astronomy, Royal Observatory, University of Edinburgh, Edinburgh EH9 3HJ, UK

Published online: 07 November 2019

1 Introduction

The original Rosetta mission was a comet-nucleus sample return and significant important studies were carried out towards this goal. A mission definition study was performed by Matra Espace and a final report issued in 1987. Two "nominal" missions were proposed one of which was to comet 67P/Churyumov-Gerasimenko. The requirements on the mission were [sic]

- Rendez-vous to an active and fresh comet with a large perihelion distance
- Characterise the surface of the nucleus into active and inactive regions, perform high resolution mapping of the sampling site and provide in-situ characterisation thereof,
- Acquire three classes of samples: (1) one which preserves stratigraphy to a depth of at least one metre and preferably three metres, (2) one containing the most volatile components, (3) surface samples intended to provide a larger volume of non-volatile component
- Store the samples until return to Earth at the temperature ambient at the sampling site, but in any case below 160 K.

In hindsight, these goals seem remarkably ambitious and it is arguable whether we are able to achieve these objectives with the knowledge that we have now post-Rosetta.

The requirements on the sample acquisition and storage were equally severe.

- The core sample shall form a continuous sample from the nucleus surface down to a desirable depth of 3 m, but not less than 1 m. It should be sub-divided and stored in several segments of approximately 10 cm in diameter in a way that preserve coarse stratigraphy [sic]. Nucleus material should not be significantly altered by the sampling process. Total mass of the core sample should be about 10 kg.
- The volatile sample should preferably be obtained from a location where the most volatile components can be expected, e.g. from the bottom of the core sample or below, down to 5 m depth. They should be stored in a totally sealed container holding 10 to 100 g.
- The bulk surface sample might be collected from the surface of the nucleus. Total mass is 1 to 5 kg.

Following the reconfiguration of Rosetta into a rendezvous mission with a landing element in 1993 (with a somewhat similar profile to that proposed for NASA's Comet Rendezvous and Asteroid Flyby mission, CRAF), the ambitions were reined back. However, it is often assumed that a sample return, recovering the science descoped from the original Rosetta, would form the ultimate goal for the next phase of cometary investigation and indeed the losing mission in the recent (2018) NASA selection for its New Frontiers programme, CAESAR (Comet Astrobiology Exploration Sample Return), had the goal of returning a sample (100–800 g) from 67P/Churyumov-Gerasimenko to Earth in 2038.

Other, perhaps less ambitious, missions to comets have been proposed in recent years. The most notable was CHopper (Comet Hopper) that became one of three missions studied in detail in the final selection round of NASA's Discovery programme in 2011, eventually losing out to the InSight mission to Mars. (There is relatively little published/refereed information about CHopper. The web site https://nssdc.gsfc.nasa.gov/planetary/text/discovery_pr_20110505.txt indicates its selection or see Hand 2012.)

The current planning for the European Space Agency science programme indicates that large scale missions to planetary targets (beyond those already selected such as JUICE) are unlikely to be feasible programmatically or financially until the late 2030s at the earliest. However, smaller, lower cost, missions looking at very specific aspects of cometary science may be possible if the technology proves feasible.

Table 1 Rosetta's comet related goals according to the Science Management Plan and a statement of achievement

	Goal	Achievement
1	Global characterisation of the nucleus, determination of dynamic properties, surface morphology and composition	Mostly, yes. The surface composition remains poorly defined
2	Chemical, mineralogical and isotopic compositions of volatiles and refractories in a cometary nucleus	The chemical and isotopic composition of volatiles has been well established. The non-volatile material considerably less so
3	Physical properties and interrelation of volatiles and refractories in a cometary nucleus	The density ratios of some gas species to bulk species were observed to be near-invariant indicating a fundamental relationship (although detailed analysis is beginning to suggest that this is too simplistic). However, this seems to be the only progress towards this goal
4	Study the development of cometary activity and the processes in the surface layer of the nucleus and in the inner coma (dust-gas interaction)	The time series of cometary activity has been reasonably well defined (with some exceptions) and the dust-gas interaction in the coma is probably close to being understood but the processes in the surface layer were not established
5	Origin of comets, relationship between cometary and interstellar material. Implications for the origin of the solar system	Compositionally, Rosetta achieved its goals for the volatiles only. However, the discussion of the shape of the nucleus and its origin/evolution has provoked significant debate

Given the range of possibilities, it is worthwhile looking at what Rosetta actually achieved, the questions that it left open, and what mission concepts could reasonably fill those gaps in our knowledge. It is not the purpose of this paper to advocate one mission concept but rather to identify possible future mission scenarios that directly address outstanding scientific issues.

We begin by looking at the major questions that have been answered by Rosetta and illustrating their importance for future missions. We then describe what Rosetta did not achieve—even in scientific topics where we expected significant steps forward. The main section follows where we look at key observations for the future. The final product from this discussion is in Sect. 5 where mission concepts are compared against the scientific return we would expect these mission concepts to achieve. It should be noted that while this plasma interaction is an interesting physical problem and its historical importance (e.g. the deduction of the existence of the solar wind through studies of cometary plasma tails by Biermann 1951) cannot be underestimated, the balance of this work is tipped towards the source of this material because it is the wish to access the "unprocessed" nucleus that forms the driving goal in cometary physics today.

2 Review of Big Questions We Have Answered

The aims of the Rosetta mission that was finally implemented were described in the Rosetta Science Management Plan (RO-EST-PL-001). The comet-related goals are listed in Table 1.

While these objectives are very broad, it is apparent that Rosetta has answered some of these goals well but others not and that the deficits are important when trying to place comets in the more general framework of solar system formation and evolution. In the sub-sections here, we look at a few of the major successes with respect to these goals.

2.1 Density and Bulk Properties

One of the major difficulties in designing the Rosetta mission, and the Philae lander in particular, was that the bulk properties of cometary nuclei were essentially unknown. Following the rapid improvement in technology in the 1990s, the combination of visible and thermal infrared measurements from Earth-orbit of cometary nuclei when remote from the Sun has subsequently provided good measures of the sizes and rotation periods which are key parameters in any rendezvous or landed mission. It might be argued that the three dimensional shape of 67P determined prior to rendezvous (Lamy et al. 2007; Lowry et al. 2012) was not really close to the remarkable bi-lobate structure actually observed. However, the importance of non-gravitational torques on solutions for the rotation period were not well recognised in advance and caution will certainly be exercised in future studies. The change of spin period through the perihelion passage was measured with high accuracy and the analysis of these data is proving to be an interesting means of analysing the total loss rate and its distribution over the nucleus (Mottola et al. 2019). The precession seems to be rather small and unlike that inferred for comet 1P/Halley, for example (Preusker et al. 2017; Gutierrez et al. 2016). Given the torques required to spin up the comet, this is perhaps a little surprising and might require some additional study. Associated work on the orbital dynamics and the relationship to the activity distribution is in progress (Attree et al. 2019) but may result in a non-unique solution. However, there is good reason to believe that the dynamical properties have been well characterised by Rosetta.

While the case for comets having low densities was very strong and values in the range of 200–600 $kg\,m^{-3}$ were widely expected for 67P, the confirmation of a density in this range was extremely useful, for both modelling of cometesimal growth and planning of future exploration. The gravitational potential resulting from the bi-lobate structure and the density is obviously complex close to the nucleus, with variations in surface gravity of $>60\%$.

The low surface reflectance found at 1P/Halley, 9P/Tempel 1 and 19P/Borrelly was confirmed and also shown to be valid down to fairly small scales. Exposures of higher reflectance material were restricted to rather small blocks or chunks (Pommerol et al. 2015b) and occasional small scale transient features (e.g. Fornasier et al. 2017).

2.2 Surface Morphology

The enormous diversity of morphology on the surface of 67P was unexpected and one of the major contributions of Rosetta to cometary science (Thomas et al. 2015b, 2018) indicating that no single process dominates the evolution of the surface.

At 67P, the evidence of airfall (also known as “dust hail” or simply “returning particles”) was overwhelming (Möhlmann 1994; Thomas et al. 2015a). It is quite apparent from the data that large areas of the surface in the northern hemisphere were covered by an almost conformal coating of dust that originated from elsewhere on the comet. The depth of this coating is unknown and almost certainly non-uniform. Much of the material in the coating has probably originated from the southern hemisphere (Keller et al. 2017).

The surface texture also indicates significant variability even in areas that should have seen the same temporal variation in insolation. This suggests that there are fundamental differences in the structure of the surface layer over relatively small length scales.

2.3 The Importance of Slow Moving, Large Particles

The presence of airfall deposits is related to a further important result. The presence of "neck-lines" in ground-based observations of dust at 67P were thought to be caused by particles, slow moving with respect to the nucleus and remaining in the vicinity of the nucleus for one or more orbits around the Sun (Fulle et al. 2004). The true significance of these observations was revealed by Rosetta. Large particles, moving at velocities close to the escape velocity, were indeed detected (Thomas et al. 2015a, 2015b; Lin et al. 2015; Agarwal et al. 2016; Ott et al. 2017) but the vast number of individual slow particles seen had not been predicted. While their presence cannot be disputed, the means by which these particles are lifted from the surface remains a subject of significant debate.

2.4 Importance and Distribution of Major Volatiles

The infrared spectrometer on Deep Impact at both 9P/Tempel 1 and 103P/Hartley 2 showed that CO_2 was strongly emitting from areas that were comparatively weak in H_2O outgassing and vice versa (e.g. Feaga et al. 2007). Observations from VIRTIS-M at 67P showed remarkably similar results considering the different objects involved (Fink et al. 2016; Migliorini et al. 2016). The ROSINA DFMS system provided further evidence that the local CO_2 outgassing rates are not in simple relationships to the H_2O outgassing rate (e.g. Gasc et al. 2017). One should not expect a linear relationship between H_2O and CO_2 outgassing simply from the thermodynamics. However, the complexity is evident from the difficulty in fitting physically and chemically more complex models to the data. Nonetheless, it has been established that both H_2O and CO_2 need to be accounted for in cometary models and that dominance of one ice over the other is probably both position and season dependent.

2.5 The Volatile Composition

The ROSINA data set of chemical species has not yet been fully exploited. However, most species previously identified in cometary comae through in situ and ground-based remote sensing have been detected (Le Roy et al. 2015). The ROSINA observations should be considered as providing the baseline for composition studies for several decades to come. Isotopic abundances in the gas phase have been measured to high accuracy (e.g. Altwegg et al. 2015; Hässig et al. 2017; Marty et al. 2017; Calmonte et al. 2017). The presence of larger than expected amounts of O_2 in the coma (Bieler et al. 2015) provides further clues to the surface formation and evolution and challenges associated models.

The ROSINA data indicates that, typically, minor species "follow" one of the bulk molecules in that the density ratios are roughly invariant with respect to either H_2O, CO_2, or O_2 although detailed investigation suggests more subtle differences are present (M. Rubin, pers. comm.). While this goes towards goal 3 in Table 1, the physical interrelationships have not been addressed at this stage although there are good grounds to assume that this can be derived from the existing data.

2.6 Thermal Inertia

Modelling of the surface temperatures of cometary nuclei were pointing towards low thermal inertia although there was potential for misinterpretation in observations acquired during fast flybys (Groussin et al. 2013; Davidsson et al. 2013). The 67P data clearly show that low values of thermal inertia are present and that it is probably varying across the object (Attree et al. 2018). To first order this variability ought to be unsurprising given the observed morphology. Airfall should lead to relatively fluffy, porous, surfaces that should be thermally insulating whereas the more rock-like appearance of other surface elements would be consistent with a higher thermal conductivity. However, the low bulk density of the nucleus suggests that even the consolidated material is highly porous (>70% perhaps) and thus, even at shallow depths below the surface (e.g. >20 cm), diurnal temperature variations should be very modest.

2.7 Tensile and Compressive Strength

All indications are that the larger scale tensile strength of nucleus material is very low and probably below 20 Pa in most cases (Attree et al. 2018). However, it is not clear how this value increases as the scale length is reduced. Local compressive strengths are potentially much higher as indicated by the shallowness of the depressions in the surface made by the Philae lander on first impact (Biele et al. 2015). The MUPUS results indicate a much higher compressive strength material just below the surface (Spohn et al. 2015). There is no universal relationship between the compressive and tensile strengths of materials but the difference between them as measured at 67P is remarkable if confirmed. The low bulk tensile strength of comets had been inferred from the break-up of comet Shoemaker-Levy 9 (Asphaug and Benz 1996) but the evidence of the stresses on the nucleus arising from the rotation and spin-up, seen in the form of cracks in the neck region of the nucleus, has clearly illustrated a mechanism for cometary splitting and other phenomena associated with comet break-up (El-Maarry et al. 2017).

2.8 Seasonal Processes

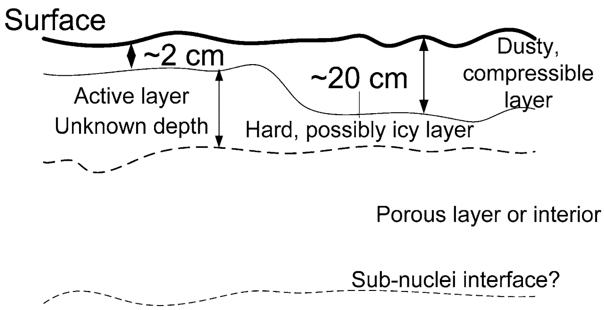
The concept of cometary obliquity playing a role in coma and surface evolution was widely discussed after the Giotto encounter with comet 1P/Halley when it was observed that the major dust jet was not directed towards the Sun but roughly aligned with the pole of initially derived rotation axis and around 60 degrees from the comet-Sun vector (e.g. Keller 1990). The Rosetta observations have been instrumental in further demonstrating the importance of seasonal processes. In addition to the importance of south-north dust transport, Fornasier et al. (2015) demonstrated surface colour variations dependent upon the annual cycle. The changes in the relative abundance of the major species when the Sun crossed the equator (Gasc et al. 2017) also points to more complex relationships than heretofore discussed.

2.9 Some Knowledge of Depth Structure

While the internal structure of the comet beneath the visible surface remains largely unknown (see below), some measurements have increased our knowledge. Brouet et al. (2016) showed that CONSERT and SESAME-PP data indicate that the porosity increases with the increasing depth in the small lobe of the nucleus (see also Ciarletti et al. 2017).

There is strong evidence of a layering in the uppermost parts of the nucleus from optical remote sensing. A controversial aspect of this observation is whether this layering is a large-scale property of the nucleus and related to its formation (Massironi et al. 2015) or whether it is a shallow phenomenon produced through cometary evolutionary processes such as dust sedimentation and thermal loading (Sunshine et al. 2016).

Fig. 1 Schematic diagram attempting to reconcile the information we currently have of the interiors of cometary nuclei



Combined with the MUPUS measurements and the absence of evidence of large scale internal voids, obtained with the radio science experiment (Pätzold et al. 2016, 2019), we obtain a picture of the shallow interior as seen in Fig. 1. There are many uncertainties in this diagram but the key thing we have learnt is that more porous material with limited thermal processing is close to the surface. Hence, the original Rosetta requirement of 3 metre penetration into the interior to access "fresh" material is unlikely to be necessary. However, the possible presence of a less porous and possibly icy sub-surface layer with considerable compressive strength implies that the fundamental problem of anchoring a lander system remains challenging.

2.10 The Relative Contributions of Quasi-Continuous and Outburst-Like Activity

Outburst phenomena have been studied in detail by several authors (e.g. Agarwal et al. 2017) in several ways (e.g. Shi et al. 2017). However, it needs to be emphasised that the most of the emission from the nucleus is quasi-continuous. The dust and gas emission is roughly reproduced on a diurnal cycle with smaller outbursts (with notable exceptions) superposed on this distribution. The similarity of the gas density measurements in the coma to models of a purely insolation-driven coma (Bieler et al. 2015) served initially as a reasonable approximation showing that outburst phenomena are not dominant. As details were more rigorously investigated, it became clear that this model was too simplistic and that non-uniqueness in solutions to the distribution of production at the surface itself was a major problem for the interpretation of the observations. Nonetheless, the basic reproducibility, the consistency with analytical descriptions (Gerig et al. 2018; Zakharov et al. 2018), and the agreement when linking space-based and ground-based measurements of the dust emission (Gerig et al. 2018) gives considerable confidence that the physics of the outflow beyond 5 km from the nucleus is broadly understood. Closer to the surface, the situation is far less clear.

3 What Did We Not Get That We Should Have

Rosetta was a successful mission that collected about 220 GB of scientific data. However, as indicated in Table 1, not all physical and chemical properties that would be essential for the deep understanding of the comet could be derived. There are several reasons for this situation.

(a) Although there were 21 experiments onboard of Rosetta and its lander Philae (Glassmeier et al. 2007) they did not cover all desirable measurements. For example, a thermal IR detector or spectrometer, as has been flown on other planetary missions (e.g. Christensen et al. 2004) was not part of the Rosetta payload. (An instrument was proposed but not flown because of budget constraints.) Therefore, low surface temperatures could not be measured and well-resolved temperature and thermal inertia maps could not be derived.

(b) Caution exercised because of the dust environment of the comet affecting the star trackers and the lack of suitable compromises between the different requirements of the instruments, limited the outcome of some experiments. Near perihelion distances of several 100 km from the nucleus and near terminator orbits led to high phase angles and poor resolution that was not optimal for most of the experiments onboard.

(c) Not all scientific instruments worked as planned. VIRTIS-M failed in April 2015 (Ciarniello et al. 2016), before perihelion. Possibly more significant, however, was the malfunction of the Philae lander. Unfortunately, when Philae first touched the comet surface the anchoring harpoons did not fire and a cold gas system, intended to press the lander to the surface, did not work. As a consequence, Philae lifted off again and only came to rest after a "hop" of about 2 hours at a location almost 1 km from the originally targeted site, "Agilkia", at a place subsequently named Abydos (Biele et al. 2015). Philae could be operated, telemetry was received, but the lander was not anchored and in an undefined attitude relative to the local surface (Ulamec et al. 2016).

When looking in more detail the following topics have been compromised because of limits on the available instrumentation or their performance.

3.1 Small-Scale Surface Temperature and Thermal Properties

Several Rosetta experiments were designed to measure surface and near surface temperatures (VIRTIS, MIRO on the spacecraft, MUPUS and SESAME on the lander, see Table 2) to derive thermal properties of the ground.

Generally, temperature measurements in space are challenging. With remote sensing one detects the IR flux (or equivalently the brightness temperature) and has to retrieve kinetic temperatures by model assumptions taking the emissivity and roughness of the surface into account. This can result in considerable errors. Additionally, measurements in the near infrared (VIRTIS-M) are contaminated by reflected solar radiation (Keihm et al. 2012). Furthermore, its ground resolution at a distance of 100 km was several tens of metres which resulted in a nonlinear average of very different temperatures in the field of view with large and small scale topographic features and compositional heterogeneities. The same is true for MIRO measurements and, additionally here, both electrical and thermal properties control the signal in such a way as to make the interpretation even more challenging. MUPUS results are limited since the penetration of PEN into the surface failed (Spohn et al. 2015) and because the complex environment of the accidental landing site is not fully understood (Groussin et al. 2019).

The kinetic temperature is a basic physical quantity that gives information on thermal properties of a surface. But Rosetta did not provide precise high resolution maps of kinetic temperature at the surface over a diurnal cycle. The absence of night time measurements, as a consequence of the orbit and the lack of a thermal infrared instrument that could measure both low temperatures and that was not affected by sunlight reflected from the surface, contribute to this issue. Consequently, thermal conductivity or thermal inertia were derived with large error bars and at low spatial resolution only (Groussin et al. 2019 and references therein).

Table 2 Rosetta instruments to measure temperatures on the comet

	VIRTIS-M	MIRO	MUPUS-TM	MUPUS-PEN	MUPUS-ANC-T	SESAME
Measurement principle	IR spectral flux from surface	Microwave flux	IR flux from surface	16 sensors for contact temperature up to 32 cm depth	Contact temperature sensors in Philae anchors up to 1.5 m depth	Contact temperature sensors in Philae's feet
Wavelength range	0.95–5.0 µm	0.5 mm and 1.6 mm	5–25 µm	–	–	–
Resolution	0.86 arcmin	7.5 arcmin and 23.8 arcmin	40 deg	–	–	–
Challenges/ Issues to derive kinetic temperatures	Instrument failure in 03/2015, Model dependent kinetic temperature, contamination by reflected light	Model dependent kinetic temperature, dependence on (unknown) electrical soil parameters	Model dependent kinetic temperature environmental conditions only partly known	Failed to penetrate	Failed due to malfunction of the anchors	Limitation of usable temperature range due to HW issues
Range	Global	Global	Local	Local	Local	Local
References	Coradini et al. (2007)	Gulkis et al. (2007)	Spohn et al. (2007)			Groussin et al. (2019)

3.2 Deep Interior

For the first time, a mission was able to collect first-hand information about the internal structure of a comet nucleus. Unfortunately, Philae's unfavourable landing site and attitude strongly limited the quantity and quality of the data collected by the two instruments—the CONSERT radar, see Kofman et al. (1998, 2007) and the permittivity probe SESAME-PP, see Seidensticker et al. (2007)—designed to characterise the nucleus electrical properties at depth (Groussin et al. 2019). Of the five electrodes of SESAME-PP (three in the lander's feet, one on MUPUS PEN, and one on APXS), only the ones in the feet could be used because APXS did not reach the comet's surface and there were operational constraints at Abydos.

Only very few exploitable measurements were acquired at Abydos (Lethuillier et al. 2016) during the First Science Sequence (FSS) with only three electrodes and a questionable contact of one of the lander feet with the nucleus surface. In addition, no absolute reference measurements were performed correctly during the SDL (Separation Descent Landing) phase because of electromagnetic interference. Despite all these shortcomings, a lower bound of the real permittivity value for the first metre below the lander was estimated that provided a constraint on the porosity of the sounded area (Lethuillier et al. 2016). A comprehensive series of measurements performed for different electrode configurations would have allowed characterisation and analysis of spatial variations of the electrical properties around the lander down to 1 or 2 metres, possibly including the imaginary part of the permittivity (linked to losses in the matter).

The CONSERT radar was designed to perform tomography of the whole nucleus thanks to a series of orbiter's trajectories optimised with respect to the lander's position. However, this was not achieved during the FSS (First Science Sequence). Furthermore, even though circular polarisation was used to minimise the mismatch between the orbiter's and lander's antennae, the radiation pattern of Philae's antennae was significantly modified by the non-optimal attitude of Philae and the fact that one antenna was probably in contact with the nucleus. Consequently, only part of the nucleus's small lobe has been sounded and characterised. On the detected signals, only the propagation delays and the shape of the received pulses have been analysed and provided an average value for the real part of the permittivity (Kofman et al. 2015) and some hints about the spatial variations (Brouet et al. 2016; Ciarletti et al. 2015) and the limited heterogeneity inside the sounded area (Ciarletti et al. 2017). The interpretation of the received amplitudes would have brought further constraints on the nucleus composition that have already been obtained (Herique et al. 2016) but would require a better knowledge of the Philae's antenna radiation pattern in the actual local environment.

3.3 Activity

While outburst phenomena have been catalogued (Fornasier et al. 2018), there remains little understanding of how the (dominant) quasi-continuous activity proceeds. It is this topic above all that has been the subject of most frustration within the Rosetta community.

The "symptoms" of cometary activity could be observed by Rosetta over many months but the microscopic observations to be achieved by Philae and designed to shed light on the mechanisms of activity did not take place. Close-up images by CIVA and ROLIS show the surface structure of Abydos and (although from a greater distance) Agilkia in great detail. However, no direct sign of ongoing activity was found (Bibring et al. 2015; Mottola et al. 2015; Schröder et al. 2016). In any case, all images taken by the lander cameras were acquired from the time between November 12 and 14, 2014 at a heliocentric distance of 3 AU when activity was not expected to have been significant.

The absence of observations constraining the processes leading to activity is arguably the biggest single issue left unaddressed by Rosetta. The uncertainty has, if anything, been increased by the observations of particles, considered to be larger than liftable by gas drag alone, above the surface and evidence that large (20 metre diameter) boulders have been moved across the surface (Agarwal et al. 2017; El-Maarry et al. 2017). Concrete progress in this area is totally absent and it appears that the only way to address this properly is to study the microphysics of the active region/layer.

3.4 Innermost Gas and Dust Comae Properties and Surface Relationships

The proximity of the Rosetta spacecraft to the nucleus was expected to provide detailed information on the gas and dust dynamics in the inner coma. Unlike previous fly-by missions, the rendezvous nature of the mission was expected to ensure a steady stream of data at different positions in the coma leading to strong constraints on the gas and dust flow. Indeed, significant steps forward were achieved. However, it has also become apparent that interpretation of the acquired data is not entirely straightforward.

Three instruments were expected to make the most significant contributions to the definition of the neutral gas flow field of the major species. The COPS sensor on ROSINA determined the gas density at the spacecraft and there remains some hope that velocities might also be derived in the near future (Tzou 2017). The VIRTIS instrument, and particularly

VIRTIS-M, obtained 2D maps of the H_2O and CO_2 distributions using IR imaging spectroscopy until the cryo-cooler failure in March 2015. The MIRO microwave spectrometry obtained line-of-sight measurements of the H_2O density, temperature, and velocity (Gulkis et al. 2007, 2015).

In all cases, there are difficulties in inversion of the data to provide unambiguous descriptions of the flow. COPS provides accurate measurements but only at the spacecraft and, for much of the mission, the spacecraft was in near-terminator orbits. In the terminator geometry, the contribution to the gas flow field from lateral expansion of gas from the near sub-solar regions is significant with strong gradients. Furthermore, it has been shown (Liao 2017) that lateral expansion will smooth out source inhomogeneities on scales up to the mean free path and hence the COPS data cannot be used to infer surface source distributions accurately. MIRO can make up for this deficiency, in principle (Marschall et al. 2019), but the inversion of the measured lines is far more complicated than in a bound atmosphere application and is compromised by the relatively broad beam width. One important aspect that might yet be resolved is the temperature of the gas at source which may be higher than the free sublimation temperature as a result of interaction between the gas and the surface layer(s). The VIRTIS measurements were limited in number and do not give flow velocities.

It is necessary to use these data sets together to constrain models (e.g. Marschall et al. 2019; Tenishev et al. 2016) of the surface activity distribution. However, from the work so far, it is not obvious that a satisfactory unique solution can be obtained even for optimum cases.

The dust distribution within the inner coma relies almost exclusively on the 2D imaging of OSIRIS with models using the size distribution derived from GIADA and COSIMA measurements (with OSIRIS looking at the largest particles). While the dust outflow has been shown to be equivalent to a free-radial outflow at distances greater than 12 km from the nucleus on average (Gerig et al. 2018), there are significant deviations in some cases that remain to be investigated. Furthermore, the dominant factors influencing the deviations from 1/r closer than 12 km to the surface are still unclear although acceleration is obviously of major importance (Zakharov et al. 2018). The surface source relationship between the gas and dust remains to be clarified although Tenishev et al. (2016) has suggested that the dust source distribution is different from the gas source distribution on larger scales which is clearly a significant problem for activity modelling.

3.5 Surface Composition

Rosetta included several instruments to analyse cometary matter. The ROSINA and COSIMA instruments obtained numerous excellent mass spectra for both gas in the coma and individual dust grains captured in the immediate vicinity of the nucleus (Altwegg et al. 2017; Hilchenbach et al. 2016). The imaging IR spectrometer, VIRTIS, mapped the entire surface of 67P in the wavelength range 0.25 to 5 µm (Filacchione et al. 2019) and found dehydrated, refractory, and organic-rich material on the surface—something that had been expected on the basis of previous observations going back to the 1980s (e.g. Chyba and Sagan 1987; Chyba et al. 1989). However, the exact composition or geometry of the molecules (notably any chiral inhomogeneity) could not be distinguished by remote IR spectroscopy and remains undetermined. Furthermore, VIRTIS results characterise the surface. But this is not necessarily representative of the bulk composition of the nucleus.

One of the main reasons leading to the proposal and development of a lander for Rosetta, was the aim of analysing (quasi-)pristine material from the comet surface and sub-surface (Ulamec et al. 1997; Wittmann et al. 1999; Biele and Ulamec 2008). The payload of Philae included four instruments, dedicated to this aim: APXS (an alpha-particle fluorescence spectrometer, Klingelhöfer et al. 2007), two evolved gas analysers (EGA's), COSAC and Ptolemy, each including a mass spectrometer and a gas-chromatograph (Goesmann et al. 2007, 2014; Wright et al. 2007), and SD^2, a drill and sampling device, to feed the ovens of the EGA's (Ercoli-Finzi et al. 2007). The camera system CIVA included a visible and IR microscope (CIVA-M), intended to image the sampled material in dedicated ovens with windows (Bibring et al. 2007).

Immediately after the first touchdown at Agilkia, the Philae system started a pre-programmed FSS, including measurements with the mass spectrometers of both evolved gas analysers, COSAC and Ptolemy, in "sniffing mode". As it appears, some surface material was introduced into the venting systems of the instruments, where excellent mass spectra could be obtained with both instruments (Goesmann et al. 2015; Wright et al. 2015). However, no gas chromatography was performed in this phase.

During an adapted FSS, an attempt was made to sample surface material, deliver it into a COSAC oven, and perform a measurement of the composition of the volatile fraction matter close to the surface with the gas-chromatograph. Although the system worked well, no sample could be obtained and the oven stayed empty as the SD^2 drill penetrated into a cavity and never touched ground (Di Lizia et al. 2016).

Ptolemy was operated after about 50 hours at the comet surface, using an oven designed to capture cometary gas onto a cold molecular sieve reagent (Comet Atmosphere Sample Experiment, CASE). The oven was heated to 200 °C, but unfortunately, the sample gas pressure was too low to flow through the GC columns (Morse et al. 2016).

As the ovens stayed empty, no attempt was made to operate CIVA-M, so no close-up IR imaging, which could have given information on the mineralogy of individual surface grains, was performed. As with SD^2, the APXS instrument did not touch the surface of the comet and no useful alpha/x-ray spectra have been obtained.

Shortly after the FSS, Philae went into an unplanned hibernation. Despite "waking-up" in June 2015, all attempts to command the instruments and start long term science investigations, turned out to be unsuccessful (Ulamec et al. 2016, 2017). Hence, the expected results regarding analyses of the cometary surface composition failed to materialise.

3.6 Some of the Properties of Cometary Dust

Cometary dust particles have been analysed in the laboratory following the Stardust mission to comet Wild 2. The atomic composition has been established in situ on mission to 1P/Halley and by the COSIMA experiment on Rosetta. Hence the mineralogical composition of cometary material has been fairly well established and the mineral to organic ratio (55:45) has been determined (Bardyn et al. 2017). However, the compositional studies have not provided details on the molecular composition of the refractory component and it may yet prove difficult to deduce complex molecules in the gas phase if the fracture patterns in the mass spectrometers prove challenging to determine.

Perhaps more fundamentally, the Rosetta observations have opened issues that might have been thought to be closed. The Giotto dust detection systems provided a complete set of observations from around 10^{-20} kg, corresponding to radii of around 0.02 microns, upwards (e.g. McDonnell et al. 1991). The Rosetta instrumentation provided no direct measurements of particles densities for particle sizes less than about 14 microns but also indicated the presence of non-escaping particles in the centimetre size range. This has led to enormous debate on the size distribution of both escaping and non-escaping particles within the nucleus and the relative significance of different particle regimes. Furthermore, the physical properties (e.g. porosity and structure) remain issues of discussion. The in situ measurements do suggest that large particles dominate the mass loss (Merouane et al. 2016) but there are considerable uncertainties. And while in situ measurements are admittedly challenging, the complete absence of more straightforward high phase angle (low scattering angle) remote sensing data requested in proposals in 1994 is purely down to the implemented spacecraft operational profile. This is not a moot point because the dust distribution function is a necessary component of refractory to volatile ratio calculations.

3.7 Summary

With respect to the goals seen in Table 1, we can conclude that several have been broadly met while others were compromised by various issues with the spacecraft and its instrumentation. The nucleus of 67P has been characterised, much has been learnt of morphology and the dynamical properties have been established. The surface composition, however, is not well understood and one can only really say that organics are present—something that was clearly established 30 years ago at 1P/Halley. It is improbable that the composition can be accurately determined by remote sensing leaving a repeated attempt at in situ analysis or sample return as the two operational techniques available to make further progress. The lack of solid information on the mineralogical and chemical composition of refractories is also present as part of goal 2 (Table 1) and similar statements apply. Here, however, the excellent knowledge of the gas composition gives us confidence that the basic volatile composition is known although the variability and the changing composition with illumination conditions remains to be understood in detail. To a large extent, this is a consequence of the major deficiency in Rosetta data—namely the absence of meaningful constraints on the physical properties of the surface layer and the interrelationship of volatiles and refractories at depth. This forms an important input to solar system formation models and is also directly related to how cometary activity (and subsequent evolution) develops. Our knowledge of the processes in the surface layer (goal 4) have not really been advanced by the mission and we continue to suppose that effects such as sub-surface sublimation, recondensation in the interior and amorphous-crystalline transitions could have significance without having major additional input to the discussion. Hence, the physical structure and composition of the surface layer to a depth of 1 metre and the inhomogeneity of this layer across the surface remain key questions after the mission.

4 Key Observations for the Future

4.1 The Depth Profile (the First 2 Metres)

While the Rosetta observations have provided hints on the structure of surface layers and specifically the porosity, the difficulties with Philae essentially compromised the goal of looking at the interrelation of volatiles and refractories and their variation with depth at intermediate scales. The primary goals would be

- to measure the density of cometary material with depth
- to establish the refractory to volatile ratio with depth
- to determine the volatile composition with depth

These three quantities would provide us with several pieces of information that are blocking study of cometary activity, namely

– the depth and density of the uppermost inert layer (if it exists)
– the changing volatile mixing ratio with depth and detection of a sub-surface recondensation layer
– the determination of the positions of species-specific sublimation fronts (should they exist)
– the depth at which internal properties are no longer influenced by the irradiation of the surface

It should be noted that models have been developed that purport to derive these quantities but none of these have actually been measured to confirm and/or constrain the models. It is also notable that coring down to at least 1 metre and preferably 3 metres was the initial target of the Rosetta mission when it was still a sample return mission in the 1980s. It is perhaps telling that we have not been able to refine this significantly other than to confirm what we already knew.

4.2 Microphysics of the Surface Layers

It is evident from the work on Rosetta data that our understanding of the microphysics of the surface and sub-surface layers remains rudimentary. This has left two major uncertainties in our understanding of comets.

First, we do not know how the volatile component is associated with the refractory component of cometary material. This is vital to understanding how comets formed and may ultimately provide key information on the solar system formation process. One can envisage ices surrounding or encapsulating the dust component, ices within dust matrices, ices as a component isolated from the refractories and so on. There is no strong evidence supporting any of these models.

Second, the thermophysical behaviour of the surface and sub-surface layers remain inadequately constrained. We have values for the thermal inertia but the thermal conductivity and heat capacity are unknown, the importance of gas transport and re-condensation are unknown, and the refractory to volatile ratio inside the nucleus remains a subject of fierce debate. Without these, models of cometary evolution are, at best, poorly constrained.

Hence, one of the primary objectives for future missions must be improved knowledge of thermophysical parameters since data interpretation and our understanding of cometary activity heavily depends on the output of thermophysical computer simulations of the upper cometary surface layers ($\leq$ 1 m). These parameters strongly depend on microphysical details of the cometary surface, such as e.g., the material composition, the morphology of the material (structure, arrangement of the particles, coordination number, void space) and the mixing of the different components (silicates, organics and ices). Besides the thermal modelling aspect, also the macroscopic behaviour of the cometary surface is influenced by the microphysical properties of the material, such as the tensile strength (Gundlach et al. 2018), compressive strength (Lorek et al. 2016; Schräpler et al. 2015), and the thermal conductivity (Gundlach and Blum 2012). However, the degree to which we can provide data on these topics needs to be traded against the complexity of method required to get that data.

Possible scenarios aiming to investigate the microphysical properties of cometary surfaces are illustrated in Fig. 2. The concepts are given in increasing order of complexity. Level A aims at measuring the material composition and improving upon Rosetta (Bardyn et al. 2017) and could dramatically reduce the number of free parameters of thermophysical models. In level B, the morphology of the upper surface layers (0.25 m) could be investigated by carefully acquiring samples without destruction. Mechanical alteration can be avoided by

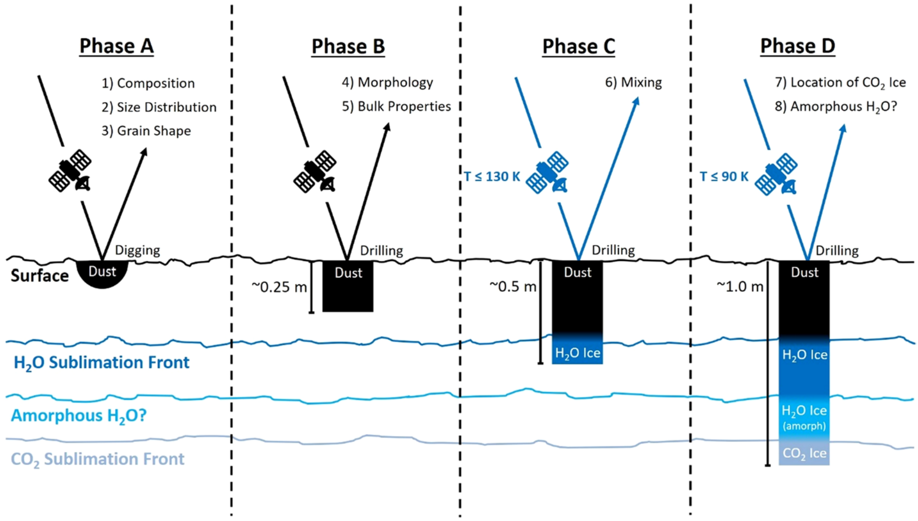


Fig. 2 Possible concepts designed to study the microphysical properties of cometary surfaces. Level A and B could be conducted without cooling of the sample and would therefore be simplest to implement. In contrast, the aim to study the microphysical properties of the volatile components (levels C and D) requires cooling of the samples during sampling, transport and measurements

careful and slow drilling. Levels A and B could be performed without the need for cryogenic sampling, whereas sampling the cometary surface (0.5 m) at low temperatures (≤ 130 K) to avoid thermal alteration is a further step in complexity. Because of the relatively high temperature, this scenario would only enable the investigation of the non-volatile components and water ice. The final sample acquisition level, level D requires very low temperatures (≤ 90 K) to provide material from a depth of >1 m. This scenario provides the possibility to study the location of CO_2 ice beneath the surface and the existence of amorphous water ice.

The microphysical properties of the cometary surface to be studied can be summarised as follows:

(1) *Composition*[1] of the material (level A)
(2) *Size distribution* of the grains (level A)
(3) *Shape* of the grains (level A)
(4) *Morphology* of the material, i.e., porosity, coordination number and void space (level B)
(5) *Bulk properties* of the building blocks, e.g., specific surface energy, Poisson's ratio, Young's modulus (level B)
(6) *Mixing* of the different components (non-volatile materials and water ice) (level C)
(7) Location of *carbon-dioxide ice* (level D)
(8) Existence of *amorphous water ice* (level D)

These properties and the difficulty of determining them illustrate the challenges that face surface landed missions.

[1] Knowledge of the material composition can be used to infer the bulk properties of the material, such as the specific surface energy, the Poisson's ratio and the Young's modulus by laboratory experiments conducted with analogue materials.

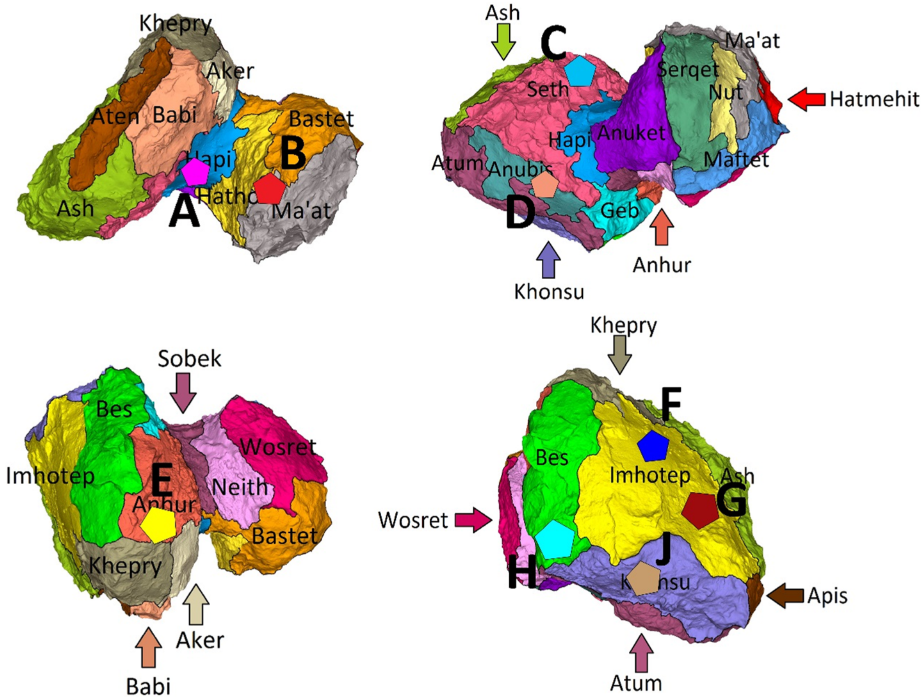


Fig. 3 The region definition on 67P with general areas of major local interest marked as polygons

4.3 Local Inhomogeneity: Comparisons at Several Local Sites

It is apparent from the surface morphology of 67P and the variations in activity (both in magnitude and composition) with position that inhomogeneity in longitude and latitude on the nucleus are present. The variability evident at 9P/Tempel 1 was perhaps less extreme but nonetheless present. There remains considerable doubt whether this inhomogeneity is primordial or evolutionary. Hence comparisons of areas of different morphology and/or morphological context are highly desirable.

For 67P, the diversity is so large that selecting a limited number of regions of interest becomes a challenge in itself. In Fig. 3, 10 sites have been marked that could justify mobility. A comparison of the surface layers of the smooth, relatively inactive, Imhotep region (site F) with the smooth, highly active, Hapi region (A) would clearly be of interest while comparing the dust-covered plains areas of the north (site B) with the dust-poor region of the southern hemisphere (sites G and J) would also have considerable scientific merit. Site B is near a region now known to have become strongly active for multiple rotations of the nucleus. Site C is the Aswan area where a cleaving and collapse of a cliff was seen (Pajola et al. 2017). Site D is in Anubis and is an area that showed surface changes similar to those seen in Imhotep and would therefore provide a comparison with site F. The Anhur region (site E) shows multiple morphologies and activity that can be compared with the adjacent Bes region (site H). H is where ices/bright material was exposed (Fornasier et al. 2017) during the approach to perihelion while G is an area that shows circular structures similar to those observed on Tempel 1 and is very different from the adjacent smooth site F.

All of these sites can provide a good case for in situ investigation because one must expect that there are physico-chemical reasons to explain their morphological diversity. The conclusion here is that mobility or the use of multiple-landed assets would have a strong scientific rationale.

4.4 The Deep Interior

The results obtained by the CONSERT radar (even if operated in very unfavourable conditions) demonstrate the unique capability of radars to provide information about the internal structure of a comet nucleus. CONSERT was operating at low frequency (90 MHz) to maximise the penetration inside the nucleus at good spatial resolution while still keeping the antennas size reasonable. This frequency range allowed analysis of potential structures larger than 10 metres in size. The use of higher frequencies would give access to smaller structures and thus provide better constraints on the nucleus building blocks sizes. Since the data collected by Rosetta indicate a contrast in physical properties between the shallow subsurface at Abydos and Agilkia, and the deeper internal structure, it would be quite interesting to get a global description of the shallow subsurface (over a few metres/tens of metres) which could be provided by a monostatic radar operating in reflection from orbit with no need of a lander (see, for example, Herique et al. 2018).

4.5 The Nature of Complex Organics and Maintaining Integrity

The isotopic, elemental, chemical, and chiral composition of non-volatile material, including complex organic material was not established. The elemental composition of ejected dust was found with COSIMA but the composition of complex organics, for example, remains unknown. Clearly, any discussion of comets bringing complex organics to the inner solar system and their participation in the evolution of life requires knowledge of the composition of these organics and it is fully apparent that the optimum way to address composition is by using the power of Earth-based analytical laboratories. Remote-sensing approaches are totally inadequate whereas in situ analysis remains technically challenging and limited by spacecraft resources. It is this aspect that forms the strongest argument for sample return.

Analytically, we are in a far better position now than 20 years ago with recent decades having seen both progressive increases in performance of instrumentation, huge increases in computer power and ease of use, and breakthroughs such as the introduction of nano-SIMS technology, the spread of con-focal microscopy and sub-micron resolution X-ray microscopes as well as the greater availability of synchrotron-based techniques.

Laboratory analysis (especially of the mineralogy, chemistry and isotopic composition) of solar-system and extra-solar material has been enormously important in furthering our understanding of the origin and evolution of the solar system, as well as shedding light on the nucleosynthetic processes in several types of star. Using samples returned from the Moon, as well as meteorites likely to have come from a variety of parent bodies (including Mars and perhaps the asteroid Vesta), we have been able to determine the age of the Earth and the solar system, the timescales for the dynamic evolution of the solar system, and the timescale over which liquid water existed on early planetesimals. The power of laboratory instrumentation, and the advantage of having samples on Earth, is shown by the way in which lunar samples returned almost 50 years ago are still leading to fresh insights. If we had instead relied solely on in situ analysis of the Moon with 1960's technology, our understanding would be a fraction of what it is today.

The two major issues with returning to Earth are connected to evolution of the sample during the sampling process and the return trip and the effects on the sample during reentry. The latter in particular is a significant problem for attempts to acquire undisturbed cores. The forces due to deceleration on re-entry will undoubtedly compromise the sample's integrity structurally, leading to mixing between products from different depths. It seems apposite to conclude that, for the foreseeable future at least, an ambition to return to Earth, a cored cometary sample is highly challenging and possibly untenable. Perhaps in the future some aspects of the problem would be overcome if there was a working "Deep Space Gateway" or "Lunar Orbital Platform" of some description that would allow the sampling to be carried out in an off-world environment (where conditions of low pressures, low temperatures and low gravity would be available for exploitation). But for now, such a possibility is certainly not feasible and the original Rosetta definition team, in considering a return to the Space Station, concluded that such a scenario was potentially even more complex than return to Earth. The CAESAR approach, of sample grabbing and limiting evolution by cooling and removal of the gaseous component, was a valid compromise.

4.6 Non-local Thermal Equilibrium in the Immediate Proximity of the Nucleus and Coma Structure

Rosetta has demonstrated that constraining the spatial distribution of gas and dust sources uniquely is vastly more challenging than originally thought. And yet this remains a key question in the efforts to relate surface structure (thermal, mechanical, chemical) to activity and evolution. The observational requirements for future missions needed to break the degeneracy and relate coma gas and dust densities to surface properties are challenging.

The single point density measurements by COPS have shown the importance of this type of measurement. Local gas density measurements at multiple positions within the inner coma would have provided far more rigorous constraints on the gas flow field. In particular, continuous measurements near the sub-solar point (over periods greater than the rotation period at a cadence of <1/min) would have been particularly valuable. When coupled with a local velocity and temperature measurement (and we note here the additional importance of determining the temperature anisotropy as a constraint on the energy distributions)

Remote sensing observations of the gas distribution were obtained by Rosetta but their interpretation remains complex. In a future mission concept, the inversion of density, temperature, and velocity from remote sensing should be traded against local direct multipoint measurements to establish the optimum strategy. The critical aspect is whether the gas flow field can be inverted to produce global maps of source strength at a resolution that is sufficient to relate the production rate to surface morphologies and properties. Given the variation in surface morphology seen on the surface of 67P, the required resolution is potentially <100 m and comparable to the mean free path for modest activity cases.

The composition of evolving gases and their interaction is not widely discussed in the literature. Finklenburg (2013) looked at CO_2-H_2O interactions in highly simplified geometries and showed the importance of understanding effects in terms of the Knudsen penetration number and the momentum transfer between CO_2 and H_2O. Where simultaneous remote sensing observations of multiple species in proximity to the nucleus have been obtained, the different spatial distributions of the different parent molecules are clearly evident (Feaga et al. 2007; Filacchione et al. 2019). The relative dominance of CO_2 at some points in the coma of 67P in local measurements was also apparent (Hässig et al. 2015). As a result, obtaining density, temperature, and velocity of the major species (H_2O, CO_2 and CO) will be important in most cases.

It is usually assumed that the dust has no influence on the gas flow field when the dust optical depth is low (as was usually the case at 67P—outburst phenomena produced exceptions). Reports of sublimation above the surface have been made (Gicquel et al. 2016) and evidence of significant ice particles in an inner coma have been reported for 103P/Hartley 2 (Hermalyn et al. 2013) and hence this may not be an accurate assumption—at least in some cases. The lifetimes of pure water ice particles in the innermost coma are quite long (Lien 1990) and this may explain the evidence of sublimating grains seen in ground-based observations of C/1996 B2 (Harris et al. 1997). Consequently the volatile content of the dust within a few kilometres of the source is a key parameter for future measurements.

There are several properties of the dust that affect the dust flow field pattern in addition to the source. It is well known that particle size and shape are important. The dust size distribution remains a critical parameter in all studies of the dust flow field and its brightness at all wavelengths. The absence of direct (unambiguous) measurements of small (<14 micron) particles is a significant source of concern in establishing accurate models for 67P and it can be argued that the size distributions of larger particles are biased as a consequence of the spacecraft being almost always in a terminator orbit configuration. It is almost mandatory to resolve this problem in future missions.

Individual scattering properties of particles are also important for extrapolating local measurements to 3D distributions using remote sensing instrument. One could envisage some form of measurement that would constrain this property and provide information on the refractive index. Ivanovski et al. (2014) have shown that the rotation of particles can influence the direction of motion but it is hard to envisage experiments to establish mean rotation rates and their influence on the bulk flow.

4.7 Cross-Comet Calibration

While we have so far considered the questions that need to be answered to better understand individual comets, the wider context of using comets to understand planet formation requires comparison between comets. We need to understand what the average comet is like, which properties are the results of the unique history of individual objects, and what can be attributed to conditions in their formation regions.

The comets that we see today come from three reservoirs: The Oort cloud is the most distant, and the source of long period and dynamically new comets, while short period Jupiter family comets (JFCs) come from the scattered disc of the Kuiper Belt. The modern distinction is based on the comet's orbit (specifically its Tisserand parameter with respect to Jupiter), and splits comets into "ecliptic" comets from the trans-Neptunian region and "nearly isotropic comets" (NICs) from the Oort cloud, the latter including both long period and high inclination short period comets of the Halley type (Levison 1996). The third reservoir is the main asteroid belt, which has recently been recognised to contain a significant population of icy bodies, including the so-called "Main Belt Comets" (MBCs), whose relatively circular orbits stay within the belt (Jewitt et al. 2015; Snodgrass et al. 2017b). The MBCs have stable orbits over the age of the Solar System, and likely formed in the same region they are found now, or at least were emplaced in the belt as the giant planets were forming. We note here that China is currently working on a mission to 2016 HO3 and 133P/Elst-Pizarro that may provide further data on this somewhat bizarre class of objects (Zhang et al. 2019).

Kuiper Belt objects also likely formed close to their current distance from the Sun, although the scattered disc (as the name implies) has a mixed origin, while the Oort cloud is populated by bodies scattered out of the original Solar System proto-planetary disc. It was thought that Oort cloud objects (and therefore long period comets) had their origin in the giant planet region, and therefore formed closer to the Sun than JFCs from the Kuiper Belt (e.g. Dones et al. 2004), but the latest dynamical models suggest a greater mixing and less clear distinctions between the original source region for different comet classes (e.g. Nesvorny et al. 2017).

The isotopic ratios of various elements, and especially the Deuterium to Hydrogen ratio (D/H), can be used as a tracer of the original formation location of a comet, as it is expected that these ratios were set by the temperature when their ices condensed out of the gas in the protoplanetary disc, and therefore their location within this disc (Robert 2006). Measurement of the isotopic ratios in a number of common elements (e.g. H, C, O, N, S) for a given comet can more uniquely constrain models (Bockelée-Morvan et al. 2015). To date we only have in situ measurements of D/H in 1P and 67P (Altwegg et al. 2015), and a few other ratios from Rosetta. Instead most isotopic measurements, and indeed nearly all compositional information on cometary comae, come from remote observations with telescopes on Earth and in space. D/H measurements via high-resolution spectroscopy have been limited to the brightest comets, which are nearly all NICs, as they tend to be more active than returning short period comets. Remote D/H measurements were possible for the JFC 103P during a close approach to Earth at perihelion, using the ESA Herschel space telescope (Hartogh et al. 2011). The D/H measured in this JFC and that found by Rosetta at 67P are very different, implying a wide range within the same comet type, or possibly systematic differences between remote and in situ observation. Measurements at a larger number of comets, and at different types of comet, would be highly desirable. Lis et al. (2019) have proposed an explanation based on their observation that hyperactive comets, such as 46P/Wirtanen, require an additional source of water vapour in their comae, explained by the presence of subliming icy grains expelled from the nucleus and that these particular objects have D/H ratios in water consistent with the terrestrial value. They propose that the isotopic properties of water outgassed from the nucleus and that of icy grains may be different because of fractionation effects during the sublimation process. There clearly remain issues of interpretation here that need to be resolved.

So far we have only visited short period comets: one NIC (1P) and five JFCs (not including the spacecraft that interacted only with the distant ion tails of comets; see e.g. Neugebauer et al. 2007). It would be very interesting to visit a long period comet, especially a dynamically new one entering the inner Solar System for the first time since it was scattered to the Oort cloud, to see a more ‘pristine’ surface, but these comets pass through the accessible region of the Solar System on much shorter timescales than missions can be planned and launched. One concept that may overcome this difficulty is to have a spacecraft launched to a suitable ‘parking’ orbit, from where it can then be sent to intercept a newly discovered comet (e.g. Hewagama et al. 2018), which becomes more feasible with the expected early discoveries of inbound objects by next generation sky surveys like the Large Synoptic Survey Telescope (LSST). An implementation of this concept, Comet Interceptor, has recently been proposed to ESA as a ‘fast’ mission (a relatively low budget class of mission, launched as a secondary payload), and was selected for a 2028 launch in June 2019.[2] The other unexplored population, the MBCs, are far more accessible, with relatively circular orbits and low activity levels. Concepts to visit one of these objects have been proposed to various space agencies (e.g. Meech and Castillo-Rogez 2015; Snodgrass et al. 2018; Jones et al. 2018), but have not yet been selected for flight.

[2]Comet Interceptor is not yet described in the literature, but more details can be found at http://www.cometinterceptor.space.

There is also significant diversity within the same population of comets. Vincent et al. (2017) suggest different evolutionary ages for the JFC nuclei that have been imaged by spacecraft, but, as pointed out by Kokotanekova et al. (2018), the comets visited by spacecraft so far are all most likely 'young', as younger comets are more active and therefore brighter and easier to discover. Very evolved comets are expected to lose their volatiles and/or build up an insulating mantle, and it would also be interesting to visit a much lower activity comet, or even one of the population of 'asteroids in cometary orbits' (ACOs), which are thought to be extinct comets at the end of their evolution. As survey telescopes are becoming more sensitive, more of these faint targets are being discovered.

Modern astronomical surveys are a powerful tool in understanding comets, as they allow us to study them in very large numbers. While it is clear that spacecraft encounters provide much more detailed information, we can only ever hope to visit a tiny fraction of the total population, while telescopes can provide a broad overview. Survey telescopes themselves provide useful information on orbits of very large numbers (LSST expects to discover $> 10^4$ comets; LSST Science Collaboration 2009), allowing their dynamics to be studied, and some information on sizes and activity levels to be derived. Surveys also discover unusual objects that tell us about the variety within the population. Targeted surveys of large numbers of comets tell us about the variation in composition, through either narrowband photometry or spectroscopy, and have allowed some taxonomic descriptions to be created (e.g. carbon-depleted vs. normal abundance—A'Hearn et al. 1995). Surveys of inactive nuclei have produced size distributions (e.g. Fernandez et al. 2013) and constrain strength and density (see Kokotanekova et al. 2017, Groussin et al. 2019, this issue). The occasional appearance of a particularly bright comet allows further detail to be extracted from telescopic observations, as a variety of techniques can be employed over a wide range of wavelengths, including higher resolution spectroscopy to study gas species or investigation of the thermal emission from dust. Bright comets can also be studied for a larger part of their orbit, allowing the evolution with changing solar heating to be investigated, for example looking at the changing relative abundance of coma species (the famous 'Christmas tree' plot for Hale-Bopp; Biver et al. 1997). While much of our knowledge comes from a few particularly bright comets, which tend to be dynamically new NICs, advances in telescope technology mean that similar studies are now possible for more typical objects, especially with the anticipated launch of JWST (Kelley et al. 2016). Other well-studied comets include those visited by spacecraft, as the opportunity to make simultaneous telescopic and in situ measurements meant that large observing campaigns could be justified (Meech et al. 2011; Snodgrass et al. 2017a). Although there is still some work to do to join the details returned by spacecraft to the very large-scale view from telescopes, these observations provide the link between the focussed spacecraft results and the general properties of the broader population of comets.

4.8 Analogue Materials for Testing

It is interesting that the measurements during the KOSI experiments (Kochan et al. 1998) are still occasionally referred to. This is in part a consequence of the rather limited amount of high quality analogue testing performed in the 15–20 years that followed KOSI. This is however changing. Groups in Braunschweig (e.g. Gundlach et al. 2011), Graz and Bern (e.g. Pommerol et al. 2015a) have been particularly active in the past 10 years in looking at cometary analogues. The behaviour of analogues is sometimes rather surprising. For example, there are significant differences in the opto-mechanical behaviour of dust encapsulated in water ice as opposed to dust mixed with water ice. Analogue testing can be used to look at the release of material from a surface, how volatiles diffuse through a surface layer, how the surface texture evolves, and how different chemical species behave with respect to water ice and its outgassing. The difference between CO_2 and H_2O as a driving volatile can also be investigated.

Constructing laboratory models in a 1 g environment applicable for low g cometary cases remains challenging and may ultimately be limited in applicability. However, these laboratory models do show that the physics can be far more complicated that the simplified assumptions used in even the most sophisticated numerical studies (e.g. Marboeuf et al. 2012).

A further use of laboratory models is in evaluating sample integrity. Even if analysis is conducted in situ, the sampling process itself may affect the sample before it reaches the analytical instrument. The maintenance of sample integrity before measurement is therefore potential of importance in constructing an accurate result. Hence, analogue testing is required and should be a component of any future comet mission.

5 Cross-Table of Missions v. Goals

We refer here to the summary in Table 3.

5.1 The Coma Swarm

One of the major issues with the Rosetta mission profile as flown was the persistent use of terminator orbits combined with the large cometocentric distances flown during the perihelion passage. This has resulted in limited information in several specific areas associated with the gas and dust dynamics of the outflow and subsequent controversy.

While single point measurements of the gas density and composition by the ROSINA instrument provided a constraint on the gas flow field and composition, the non-uniqueness of the results when extending them to 3 dimensions around the nucleus has been shown to be extreme. Incorporation of other data (from the MIRO experiment for example) has been shown to be difficult because of the non-LTE nature of the flow (Marschall et al. 2019). The observations of VIRTIS-M were of insufficient resolution to provide meaningful constraints.

One approach to addressing these issues is to use a swarm of small satellites to surround the nucleus and make multi-point simultaneous measurements of the coma. The aim would be to fully characterise the 3D distribution of gas and dust including density, temperature, and composition. Each small satellite could also carry low resolution camera systems (visible and/or infrared) to support the 3D analyses. Such a mission would also allow higher accuracy measurements of production rates.

Swarms could also be useful in resolving the dust production rate issues encountered by Rosetta. It would remain to be seen how much payload could be incorporated onto each element of any one member of a swarm but the need for further investigations of dust particle properties in situ remains paramount after Rosetta. It should also be noted that sample return may lead to further information but transfer to and re-entry into the Earth's atmosphere will have influence on potentially delicate particles including thermal evolution.

5.2 The Surface Network

Inhomogeneity of the nucleus in morphology and (probably) chemistry is evident. Furthermore, there are seasonal variations that require considerably more investigation than Rosetta could afford. Hence, the scientific need to investigate and compare several areas on a comet is still there. One approach is use a surface "network". Here, multiple static landers are placed on the surface and conduct several experiments in a coordinated manner. The advantage of the network is that sounding can be conducted from one network element to another and seismic studies can also be carried out to determine the internal properties of the object. A CONSERT style system would still have advantages, however, in providing a moving element on an orbiter. However, the experiment package for each landed element might also include instruments dedicated to comparisons of the physical properties between the landing sites. Instrumentation could include microscopic imaging, miniaturised mass spectrometers and/or Raman spectrometers and penetrating thermal sensors. The technical challenges would include the anchoring to the surface and the need to study the seasonal variations by ensuring network element lifetimes are adequate to perform observations for extended periods in darkness at high latitudes.

5.3 The Surface "Rover"

In the early phase of the conceptual design of the Rosetta Lander (RoLand), the possibility of mobility by hopping was investigated (RoLand Proposal 1995; Ulamec et al. 1997). The idea was given up though, as any movement from a safe landing site was considered an unnecessary risk and mobility is difficult to combine with firm anchoring. However, any high precision landing at a specific site (e.g. within proposed active areas) is highly attractive. Consequently, mobile comet landers have been proposed. One particular concept studied in detail was the Comet Hopper, CHopper, proposed for the opportunity #12 within the NASA Discovery Program, selected as one of the three finalists but eventually not selected for implementation in 2012.

The CHopper mission would have attempted to measure cometary activity of comet 46P/Wirtanen at several (up to six) locations and various heliocentric distances. CHopper would have been a flexible spacecraft, powered by two Advanced Stirling Radioisotope Generators, ASRG's, rendezvousing comet 46P/Wirtanen and investigating several surface areas at various heliocentric distances using a propulsion system based "hopping" (Clark et al. 2008). Another Discovery proposal to investigate cometary activity was CHagall, based on ideas as proposed for CHopper. As neither CHopper nor CHagall have been selected, and Philae hardly contributed to this particular aspect of cometary science, these measurements are still to be done in the course of future missions. It is worth noting that comet sample return missions will not necessarily allow new results regarding the mechanisms of cometary activity. For this, long term high-resolution in-situ observations with cameras, mass spectrometers/pressure sensors and possibly drills are almost certainly the best approach.

Generally, mobility strategies as considered or designed for other low gravity bodies like asteroids or the Martian moon Phobos, are relevant also for comets. An overview of small bodies hoppers, including the Soviet Phobos Hopper from 1988 (PROP-F) is given e.g. by Ulamec et al. (2011); a description of MASCOT, a small mobile surface package which has been delivered by the Japanese Hayabusa 2 spacecraft to asteroid (162173) Ryugu is given by Ho et al. (2017).

5.4 The Multi-Object Fly-by

The diversity of comets has been demonstrated by imaging of nuclei during fly-bys. Comparison of Hartley 2, Wild 2, and 67P is sufficient to show this clearly. However, chemical differences are also evident. This suggests that there remains substantial justification for multi-object studies.

The juxtaposition of broad surveys versus detailed investigations of individual bright comets is analogous to the arguments for missions to fly-by many comets versus a Rosetta-like rendezvous mission. While many of the questions discussed herein require another rendezvous mission, there is also a strong desire to increase the breadth of our understanding of the comet population by visiting a larger number. The ill-fated CONTOUR mission would have visited three or four comets (Cochran et al. 2002), but failed shortly after launch. Multiple asteroid fly-by tours within the main belt have been proposed (Rivkin et al. 2015; Bowles et al. 2018), which could potentially visit MBCs, while the extended missions of the Giotto (1P/Halley, 26P/Grigg-Skjellerup), Stardust (82P/Wild 2, 9P/Tempel 2), and Deep Impact (9P/Tempel 2, 103P/Hartley 2) spacecraft show that it is also quite feasible to encounter multiple comets in near-Earth space although none of these concepts have been selected at the time of writing. Fly-by missions can address nucleus science through remote sensing, even if they return only a snap-shot at a single time, and have the potential to return compositional information on the more abundant coma species if they pass close enough with suitable mass spectrometer instrumentation. Fly-by missions necessarily trade the scientific value of a closer approach against the safety of the spacecraft making a high-speed pass through a dusty environment, but with careful orbit planning and a payload designed to return results from a safe distance, many comets could potentially be studied by the same spacecraft. The common instrumentation for each fly-by would be extremely beneficial in making detailed comparisons. Sensitive instruments are increasingly being designed to be small enough for use in micro-satellites (particularly 'CubeSats'), raising the possibility of deployable probes designed to get much closer during a fly-by, taking a higher risk but probing the inner coma. The Comet Interceptor concept (see above) makes use of such deployable probes to enable close approach investigation during a potentially very-high speed fly-by of a long period comet, while keeping the 'mothership' at a safer distance.

5.5 Advanced Impact Exhumation

The Deep Impact experiment demonstrated a method to gain access to the interior of a comet without the complexity of drilling. Impactor technologies are being further advanced through the Asteroid Impact and Deflection Assessment (AIDA) mission studies. As part of AIDA (Cheng et al. 2015), two independent spacecraft would be sent to the asteroid, Didymos. An asteroid impactor—the NASA Double Asteroid Redirection Test (DART) spacecraft—would be sent to the target and a follow-up asteroid rendezvous spacecraft, Hera (Michel et al. 2018), would observe the consequence of the impact.

The Deep Impact mission was not able to assess the impact crater accurately and while much was learnt about the impact itself and the surface of the comet target (9P/Tempel 1), there was relatively little learnt of the exposed interior. However, it is apparent that this is a means of accessing primitive material in a cost effective manner. It is also apparent that the exposure of the interior results in a relative slow change in the new surface layer properties (as shown by Pajola et al. 2017 following the Aswan cleaving event). Hence, this approach is of significant scientific interest. It would need to be established, however, how much the exposed material is modified by the impact itself and whether the properties we are most interested in (e.g. the volatile-refractory inter-relationship) are influenced by the impact process.

5.6 Sample Return

Sample return from a comet has been a "Holy Grail" for more than 30 years. Early concepts were discussed in Eberhardt et al. (1986). This is now being studied in detail with a modern approach (although coincidentally using the same acronym) through the CAESAR mission that was recently pre-selected by NASA as part of its New Frontiers programme but which lost out in the final down-selection in July 2019. The concept proposed therein was focussed very strongly on returning the sample with only additional observations that are necessary to complete the task.

The sampling approach differs significantly from the original (1980s) Rosetta concept and illustrates that "sample return" can mean many different things. In the case of CAESAR, the approach was strongly focussed on the chemistry. The sampling system is currently intended to get a sample from the surface, if necessary, by using a rotational grinding-like system. This would reduce the integrity of any sample for studies of the physical nature of the surface layer and its structure with depth. The volatile component is then allowed to outgas with the gaseous products being captured and analysed. The refractory materials are maintained at low temperature and returned to Earth.

This clearly answers one of the main outstanding issues from previous comet missions in that it determines the surface composition (under the obvious assumption that post-sampling reactions are of no importance) while the volatile composition (about which we have rather accurate knowledge already) is also assessed. However, it is not obvious that such an approach can place further constraints on the structural and physical nature of the surface layer. Hence, there will remain considerable scope for future sample return missions even if CAESAR is eventually completed successfully. On the other hand, as noted above, the maintenance of sample integrity in a physical sense through the return to Earth is likely to be extremely challenging.

For completeness, we should also note that Albee et al. (1994) proposed a coma sample return mission called Soccer as a joint NASA-ISAS mission which indirectly led to the successful STARDUST coma sample return mission within NASA's Discovery programme.

5.7 Other Targets of Relevance

While focussing on missions to active comets, there are other objects that are of relevance for cometary research that deserve some level of attention. The existence of "main-belt comets" has provoked proposals for future missions because they are easier to get to and it is clear that understanding their outgassing would contribute to cometary science although the exact relationship may not be completely obvious.

Investigation of the surface layers of "dead" comets (3200 Phaethon and 2015 TB145 have been discussed as possible examples with Phaethon now being the target of JAXA's Destiny+) would provide an important description of how activity eventually ceases. Our observations at 67P would suggest that, in some of these objects, transport and airfall of material has finally choked all activity but that relatively pristine material is close to the surface. This hypothesis could be tested. The absence of activity would make the mission far simpler if there is concern about outgassing and large dust particles in the vicinity of the object. Hence, getting at pristine material in these objects may be more straightforward than for active comets.

Observations of Centaurs, which could be objects in transition from the Kuiper Belt to the inner Solar System, would also be of major interest in view of their limited thermal evolution. 2060 Chiron is a remarkable object that could easily yield significant scientific knowledge of primitive materials. It is, of course, also known to outgas. The major drawback is that Centaurs are challenging objects to study in situ, requiring an energy source beyond solar power and significant delta-V to reach.

Trojan asteroids may also be relevant and are now the subject of NASA's Discovery mission, Lucy. Their relationship to cometary objects is, however, unclear.

Table 3 Comparison table

Mission concept	Description	Goals	Comments
The coma swarm	Multiple small satellites or cube-sats orbiting or manoeuvering around the nucleus making local measurements of the gas and dust coma	– Detailed evaluation of the gas and dust dynamics in 3D – Dust size distributions and their variation within the coma – Simultaneous multi-directional remote-sensing of the nucleus to monitor activity	
The surface network	Multiple small landed packages placed on the surface of the nucleus	– Determination of the interior structure through low frequency tomography – Seismic sensing of the interior – Local investigation of the surface layer structure at sub-centimetre scales	It is assumed that this concept would not allow a drilling system
The surface rover	Single mobile station traversing the cometary nucleus	– Determination of the diversity of cometary material within one object – Local investigation of the surface layer structure at sub-metre scales	It is assumed that this concept would carry a drilling system
The multi-object fly-by	Single spacecraft making multiple fast fly-bys of cometary and/or comet-like objects	– Characterisation of the diversity of comet-like objects – Imaging and detailed measurements of composition	
Advanced impact exhumation	Dual spacecraft system with an impactor and a monitoring spacecraft. Improved version of Deep Impact to view in detail the exhumed material through a rendezvous	– Evaluation of the internal properties of the target – Determination of the layer structure (if present) – Determination of the internal composition	AIDA: DART/Hera concept might be considered
Sample return	Spacecraft rendezvous and acquisition of cometary material followed by return to Earth	– Detailed laboratory analysis of cometary material	Studies through Phase A in the CAESAR New Frontiers mission but subsequently rejected. Good chemical and isotopic studies but perhaps limited physical knowledge of the material

Finally, New Horizons's observations of 2014 MU69 (Stern et al. 2019) have illustrated the importance of visiting pristine objects outside the orbit of Neptune although travel times and power sources remain challenging.

As noted in the introduction, we have effectively ignored the physics of a comet's interaction with the solar wind herein. While the study of this interaction is interesting and, for example, multi-point observations of the interaction would undoubtedly be of benefit in constraining details, it seems unlikely to us that the next mission(s) to comets will be driven by this sub-topic.

6 Conclusion

The in situ investigation of comets has taken a giant leap forward with Rosetta. On the other hand, the mission did not constrain well the activity mechanism and our knowledge of the physical properties of the surface layer remain somewhat limited. We also have major questions about the localisation of activity and the gas and dust comae within 2–3 kilometres of the surface.

It is arguable whether the original comet nucleus sample return objectives laid out in the early studies for what became Rosetta could be achieved today—even with improved technology and knowledge of the target properties. Hence, the more limited focus of NASA's CAESAR, was undoubtedly a wise approach. However, in its current form, there will still remain unaddressed issues such as the relationship between volatile and refractory material in the nucleus interior and the variability between different objects.

Various mission profiles can be considered to answer the outstanding questions. It is not the purpose of this paper to propose one over the rest (something that would be best addressed by requesting full proposals) but it is evident that several mission concepts could be competed against each other leading to optimised scientific return.

Acknowledgements The team from the University of Bern is supported through the Swiss National Science Foundation and through the NCCR PlanetS. The project has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 686709. This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 16.0008-2. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

J. Agarwal, M.F. A'Hearn, J.-B. Vincent, C. Guettler, S. Hoefner, H. Sierks, C. Tubiana, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, M.A. Barucci, J.-L. Bertaux, I. Bertini, S. Boudreault, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, J. Deller, S. Fornasier, M. Fulle, A. Gicquel, O. Groussin, P.J. Gutierrez, M. Hofmann, S.F. Hviid, W.-H. Ip, L. Jorda, H.U. Keller, J. Knollenberg, J.-R. Kramm, E. Kuehrt, M. Kueppers, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, G. Naletto, N. Oklay, X. Shi, N. Thomas, Acceleration of individual, decimetre-sized aggregates in the lower coma of comet 67P/Churyumov-Gerasimenko. Mon. Not. R. Astron. Soc. **462**, S78–S88 (2016)

J. Agarwal et al., Evidence of sub-surface energy storage in comet 67P from the outburst of 2016 July 03. Mon. Not. R. Astron. Soc. **469**, s606–s625 (2017)

M.F. A'Hearn, R.C. Millis, D.O. Schleicher, D.J. Osip, P.V. Birch, The ensemble properties of comets: Results from narrowband photometry of 85 comets, 1976–1992. Icarus **118**, 223–270 (1995)

A.L. Albee, K.T. Uesugi, P. Tsou, SOCCER: Comet coma sample return mission, in *Lunar and Planetary Inst., Workshop on Particle Capture, Recovery and Velocity/Trajectory Measurement Technologies* (1994), pp. 7–11

K. Altwegg, H. Balsiger, A. Bar-Nun, J.J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. Fuselier, S. Gasc, T.I. Gombosi, K.C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. LeRoy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Reme, M. Rubin, T. Semon, C.-Y. Tzou, H. Waite, P. Wurz, 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. Science **347**, 1261952 (2015)

K. Altwegg, H. Balsiger, J. Berthelier et al., Organics in comet 67P—A first comparative analysis of mass spectra from ROSINA–DFMS, COSAC and Ptolemy. Mon. Not. R. Astron. Soc. **469**, S130–S141 (2017)

E. Asphaug, W. Benz, Size, density, and structure of comet Shoemaker-Levy 9 inferred from the physics of tidal breakup. Icarus **121**, 225–248 (1996)

N. Attree et al., Tensile strength of 67P/Churyumov-Gerasimenko nucleus material from overhangs. Astron. Astrophys. **611**, A33 (2018)

N. Attree, L. Jorda, O. Groussin, S. Mottola, N. Thomas, Y. Brouet, E. Kührt, M. Knapmeyer, F. Preusker, F. Scholten, J. Knollenberg, S. Hviid, P. Hartogh, R. Rodrigo, Constraining models of activity on comet 67P/Churyumov-Gerasimenko with Rosetta trajectory, rotation, and water production measurements. Astron. Astrophys. **630**, A18 (2019)

O. Bardyn et al., Carbon-rich dust in comet 67P/Churyumov-Gerasimenko measured by COSIMA/Rosetta. Mon. Not. R. Astron. Soc. **469**, S712 (2017)

J.-P. Bibring, P. Lamy, Y. Langevin, A. Soufflot, M. Berthé, J. Borg, F. Poulet, S. Mottola, Civa. Space Sci. Rev. **128**, 397–412 (2007)

J.-P. Bibring, Y. Langevin, J. Carter et al., 67P/Churyumov–Gerasimenko surface properties as derived from CIVA panoramic images. Science **349**, aab0671 (2015)

J. Biele, S. Ulamec, Capabilities of Philae, the Rosetta Lander. Space Sci. Rev. **138**, 275–289 (2008)

J. Biele, S. Ulamec, M. Maibaum, R. Roll, L. Witte, E. Jurado, P. Munoz, W. Arnold, H.-U. Auster, C. Casas, C. Faber, C. Fantinati, F. Finke, H.-H. Fischer, K. Geurts, C. Güttler, P. Heinisch, A. Herique, S. Hviid, G. Kargl, M. Knapmeyer, J. Knollenberg, W. Kofman, N. Kömle, E. Kührt, V. Lommatsch, S. Mottola, R. Pardo de Santayana, E. Remetean, F. Scholten, K.J. Seidensticker, H. Sierks, T. Spohn, The landing(s) of Philae and inferences about comet surface mechanical properties. Science **349**, aaa9816 (2015)

A. Bieler, K. Altwegg, H. Balsiger, A. Bar-Nun, J.-J. Berthelier, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. de Keyser, E.F. van Dishoeck, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, K.C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, R. Maggiolo, B. Marty, O. Mousis, T. Owen, H. Reme, M. Rubin, T. Semon, C.-Y. Tzou, J.H. Waite, C. Walsh, P. Wurz, Abundant molecular oxygen in the coma of comet 67P/Churyumov-Gerasimenko. Nature **526**, 678–681 (2015)

L. Biermann, Kometenschweife und solare Korpuskularstrahlung. Z. Astrophys. **29**, 274 (1951)

N. Biver, D. Bockelée-Morvan, P. Colom, J. Crovisier, B. Germain, E. Lellouch, J.K. Davies, W.R.F. Dent, R. Moreno, G. Paubert, J. Wink, D. Despois, D.C. Lis, D. Mehringer, D. Benford, M. Gardner, T.G. Phillips, M. Gunnarsson, H. Rickman, A. Winnberg, P. Bergman, L.E.B. Johansson, H. Rauer, Long-term evolution of the outgassing of comet Hale-Bopp from radio observations. Earth Moon Planets **78**, 5–11 (1997)

D. Bockelée-Morvan, U. Calmonte, S. Charnley, J. Duprat, C. Engrand, A. Gicquel, M. Hässig, E. Jehin, H. Kawakita, B. Marty, S. Milam, A. Morse, P. Rousselot, S. Sheridan, E. Wirström, Cometary isotopic measurements. Space Sci. Rev. **197**, 47–83 (2015)

N.E. Bowles, C. Snodgrass, A. Gibbings, J.P. Sanchez, J.A. Arnold, P. Eccleston, T. Andert, A. Probst, G. Naletto, A.C. Vandaele, J. de Leon, A. Nathues, I.R. Thomas, N. Thomas, L. Jorda, V. Da Deppo, H. Haack, S.F. Green, B. Carry, K.L. Donaldson Hanna, J. Leif Jorgensen, A. Kereszturi, F.E. DeMeo, M.R. Patel, J.K. Davies, F. Clarke, K. Kinch, A. Guilbert-Lepoutre, J. Agarwal, A.S. Rivkin, P. Pravec, S. Fornasier, M. Granvik, R.H. Jones, N. Murdoch, K.H. Joy, E. Pascale, M. Tecza, J.M. Barnes, J. Licandro, B.T. Greenhagen, S.B. Calcutt, C.M. Marriner, T. Warren, I. Tosh, CASTAway: An asteroid main belt tour and survey. Adv. Space Res. **62**, 1998–2025 (2018)

Y. Brouet, A.C. Levasseur-Regourd, P. Sabouroux, L. Neves, P. Encrenaz, O. Poch, A. Pommerol, N. Thomas, W. Kofman, A. Le Gall, V. Ciarletti, A. Herique, A. Lethuillier, N. Carrasco, C. Szopa, A porosity gradient in 67P/C-G nucleus suggested from CONSERT and SESAME-PP results: An interpretation based on new laboratory permittivity measurements of porous icy analogues. Mon. Not. R. Astron. Soc. **462**, S89–S98 (2016)

U. Calmonte, K. Altwegg, H. Balsiger, J.-J. Berthelier, A. Bieler, J. De Keyser, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, L. Le Roy, M. Rubin, T. Sémon, C.-Y. Tzou, S.F. Wampfler, Sulphur isotope mass-independent fractionation observed in comet 67P/Churyumov-Gerasimenko by Rosetta/ROSINA. Mon. Not. R. Astron. Soc. **469**, S787–S803 (2017)

A.F. Cheng, J. Atchison, B. Kantsiper, A.S. Rivkin, A. Stickle, C. Reed, A. Galvez, I. Carnelli, P. Michel, S. Ulamec, Asteroid impact & deflection assessment mission. Acta Astronaut. **115**, 262–269 (2015)

P.R. Christensen, B.M. Jakosky, H.H. Kieffer, M.C. Malin, H.Y. McSween Jr., K. Nealson, G.L. Mehall, S.H. Silverman, S. Ferry, M. Caplinger, M. Ravine, The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. Space Sci. Rev. **110**, 85–130 (2004)

C. Chyba, C. Sagan, Infrared emission by organic grains in the coma of comet Halley. Nature **330**, 350–353 (1987)

C.F. Chyba, C. Sagan, M.J. Mumma, The heliocentric evolution of cometary infrared spectra—Results from an organic grain model. Icarus **79**, 362–381 (1989)

V. Ciarletti, A.C. Levasseur-Regourd, J. Lasue, C. Statz, D. Plettemeier, A. Herique, Y. Rogez, W. Kofman, CONSERT suggests a change in local properties of 67P/Churyumov-Gerasimenko's nucleus at depth. Astron. Astrophys. **583**, A40 (2015)

V. Ciarletti, A. Herique, J. Lasue, A.-C. Levasseur-Regourd, D. Plettemeier, F. Lemmonier, C. Guiffaut, P. Pasquero, W. Kofman, CONSERT constrains the internal structure of 67P at a few metres size scale. Mon. Not. R. Astron. Soc. **469**, S805–S817 (2017)

M. Ciarniello, A. Raponi, F. Capaccioni, G. Filacchione, F. Tosi, M.C. De Sanctis, D. Kappel, B. Rousseau, G. Arnold, M.T. Capria, M.A. Barucci, E. Quirico, A. Longobardo, E. Kuehrt, S. Mottola, S. Erard, D. Bockelee-Morvan, C. Leyrat, A. Migliorini, A. Zinzi, E. Palomba, B. Schmitt, G. Piccioni, P. Cerroni, W.-H. Ip, G. Rinaldi, M. Salatti, The global surface composition of 67P/Churyumov-Gerasimenko nucleus by Rosetta/VIRTIS. II Diurnal and seasonal variability. Mon. Not. R. Astron. Soc. **462**, S443–S458 (2016)

B.C. Clark, J.M. Sunshine, M.F. A'Hearn, A.L. Cochran, T.L. Farnham, W.M. Harris, T.J. McCoy, J. Veverka, Comet Hopper: A mission concept for exploring the heterogeneity of comets, in *Asteroids, Comets, Meteors*, vol. 1405 (2008), p. 8131

A. Cochran, J. Veverka, J. Bell, M. Belton, J. Benkhoff, A. Benkhoff, B. Clark, P. Feldman, J. Kissel, P. Mahaffy, M. Malin, S. Murchie, H. Neimann, T. Owen, M. Robinson, G. Schwehm, S. Squyres, P. Thomas, F. Whipple, D. Yeomans, The comet nucleus tour (contour); a NASA discovery mission. Earth Moon Planets **89**, 289–300 (2002)

A. Coradini, F. Capaccioni, P. Drossart, G. Arnold, E. Ammannito, F. Angrilli, A. Barucci, G. Bellucci, J. Benkhoff, G. Bianchini, J.P. Bibring, M. Blecka, D. Bockelee-Morvan, M.T. Capria, R. Carlson, U. Carsenty, P. Cerroni, L. Colangeli, M. Combes, M. Combi, J. Crovisier, M.C. De Sanctis, E.T. Encrenaz, S. Erard, C. Federico, G. Filacchione, U. Fink, S. Fonti, V. Formisano, W.H. Ip, R. Jaumann, E. Kuehrt, Y. Langevin, G. Magni, T. McCord, V. Mennella, S. Mottola, G. Neukum, P. Palumbo, G. Piccioni, H. Rauer, B. Saggin, B. Schmitt, D. Tiphene, G. Tozzi, Virtis: An imaging spectrometer for the Rosetta mission. Space Sci. Rev. **128**, 529–559 (2007)

B.J.R. Davidsson, P.J. Gutiérrez, O. Groussin, M.F. A'Hearn, T. Farnham, L.M. Feaga, M.S. Kelley, K.P. Klaasen, F. Merlin, S. Protopapa, H. Rickman, J.M. Sunshine, P.C. Thomas, Thermal inertia and surface roughness of Comet 9P/Tempel 1. Icarus **224**, 154–171 (2013)

P. Di Lizia, F. Bernelli-Zazzera, A. Ercoli-Finzi, S. Mottola, C. Fantinati, E. Remetean, B. Dolives, Planning and implementation of the on-comet operations of the instrument SD2 onboard the lander Philae of Rosetta mission. Acta Astronaut. **125**, 183–195 (2016)

L. Dones, P.R. Weissman, H.F. Levison, M.J. Duncan, in *Comets II*, ed. by M.C. Festou, H.U. Keller, H.A. Weaver (University of Arizona Press, Tucson, 2004), p. 153

P. Eberhardt, J.A.M. McDonnell, R. Reinhard, G.H. Schwehm, E. Bussoletti, M. Hechler, A. Johnstone, A.-C. Levasseur-Regourd, H.U. Keller, G.E.N. Scoon, CAESAR mission: A comet atmosphere encounter and sample return, in *ESA, Proceedings of the 20th ESLAB Symposium on the Exploration of Halley's Comet, vol. 3: Posters* (1986), pp. 243–248

M.R. El-Maarry et al., Surface changes on comet 67P/Churyumov-Gerasimenko suggest a more active past. Science **355**, 1392–1395 (2017)

A. Ercoli-Finzi, F.B. Zazzera, C. Dainese, F. Malnati, P.G. Magnani, E. Re, P. Bologna, S. Espinasse, A. Olivieri, SD^2—How to sample a comet. Space Sci. Rev. **128**, 281 (2007)

L.M. Feaga, M.F. A'Hearn, J.M. Sunshine, O. Groussin, T.L. Farnham, Asymmetries in the distribution of H_2O and CO_2 in the inner coma of Comet 9P/Tempel 1 as observed by Deep Impact. Icarus **191**, 134–145 (2007)

Y.R. Fernandez, M.S. Kelley, P.L. Lamy, I. Toth, O. Groussin, C.M. Lisse, M.F. A'Hearn, J.M. Bauer, H. Campins, A. Fitzsimmons, J. Licandro, S.C. Lowry, K.J. Meech, J. Pittichova, W.T. Reach, C. Snodgrass, H.A. Weaver, Thermal properties, sizes, and size distribution of Jupiter-family cometary nuclei. Icarus **226**, 1138–1170 (2013)

G. Filacchione, O. Groussin, C. Herny, D. Kappel, S. Mottola, N. Oklay, A. Pommerol, I. Wright, Z. Yoldi, M. Ciarniello, L. Moroz, A. Raponi, Comet 67P/CG nucleus composition and comparison to other comets. Space Sci. Rev. **215**, 19 (2019)

U. Fink, L. Doose, G. Rinaldi, A. Bieler, F. Capaccioni, D. Bockelee-Morvan, G. Filacchione, S. Erard, C. Leyrat, M. Blecka, M.T. Capria, M. Combi, J. Crovisier, M.C. De Sanctis, N. Fougere, F. Taylor, A.

Migliorini, G. Piccioni, Investigation into the disparate origin of CO_2 and H_2O outgassing for Comet 67/P. Icarus **277**, 78–97 (2016)
S. Finklenburg Ph.D. thesis, University of Bern (2013)
S. Fornasier, P.H. Hasselmann, M.A. Barucci, C. Feller, S. Besse, C. Leyrat, L. Lara, P.J. Gutierrez, N. Oklay, C. Tubiana, F. Scholten, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.F. A'Hearn, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, M. Fulle, O. Groussin, C. Güttler, S.F. Hviid, W. Ip, L. Jorda, J. Knollenberg, G. Kovacs, R. Kramm, E. Kührt, M. Küppers, F. La Forgia, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, K.-D. Matz, H. Michalik, F. Moreno, S. Mottola, G. Naletto, M. Pajola, A. Pommerol, F. Preusker, X. Shi, C. Snodgrass, N. Thomas, J.-B. Vincent, Spectro-photometric properties of the 67P/Churyumov-Gerasimenko's nucleus from the OSIRIS instrument onboard the ROSETTA spacecraft. Astron. Astrophys. **583**, A30 (2015). https://doi.org/10.1051/0004-6361/201525901
S. Fornasier et al., The highly active Anhur-Bes regions in the 67P/Churyumov-Gerasimenko comet: Results from OSIRIS/ROSETTA observations. Mon. Not. R. Astron. Soc. **469**, S93–S107 (2017)
S. Fornasier, V.H. Hoang, P.H. Hasselmann, C. Feller, M.A. Barucci, J.D.P. Deshapriya, H. Sierks, G. Naletto, P.L. Lamy, R. Rodrigo, D. Koschny, B. Davidsson, J. Agarwal, C. Barbieri, J.-L. Bertaux, I. Bertini, D. Bodewits, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, J. Deller, S. Ferrari, M. Fulle, P.J. Gutierrez, C. Guttler, W.-H. Ip, H.U. Keller, M. Küppers, F. La Forgia, M.L. Lara, M. Lazzarin, Z. Lin, J.J. Lopez Moreno, F. Marzari, S. Mottola, M. Pajola, X. Shi, I. Toth, C. Tubiana, Linking surface morphology, composition, and activity on the nucleus of 67P/Churyumov-Gerasimenko (2018). arXiv:1809.03997
M. Fulle, C. Barbieri, G. Cremonese, H. Rauer, M. Weiler, G. Milani, R. Ligustri, The dust environment of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **422**, 357–368 (2004)
S. Gasc, K. Altwegg, H. Balsiger, J.-J. Berthelier, A. Bieler, U. Calmonte, B. Fiethe, S. Fuselier, A. Galli, T. Gombosi, M. Hoang, J. De Keyser, A. Korth, L. Le Roy, U. Mall, H. Rème, M. Rubin, T. Sèmon, C.-Y. Tzou, J.H. Waite, P. Wurz, Change of outgassing pattern of 67P/Churyumov-Gerasimenko during the March 2016 equinox as seen by ROSINA. Mon. Not. R. Astron. Soc. **469**, S108–S117 (2017)
S.-B. Gerig, R. Marschall, N. Thomas, I. Bertini, D. Bodewits, B. Davidsson, M. Fulle, W.-H. Ip, H.U. Keller, M. Küppers, F. Preusker, F. Scholten, C.C. Su, I. Toth, C. Tubiana, J.-S. Wu, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, J. Agarwal, M.A. Barucci, J.-L. Bertaux, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, J. Deller, S. Fornasier, O. Groussin, P.J. Gutierrez, C. Güttler, S.F. Hviid, L. Jorda, J. Knollenberg, J.-R. Kramm, E. Kührt, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, S. Mottola, G. Naletto, N. Oklay, J.-B. Vincent, On deviations from free-radial outflow in the inner coma of comet 67P/Churyumov-Gerasimenko. Icarus **311**, 1–22 (2018)
A. Gicquel et al., Sublimation of icy aggregates in the coma of comet 67P/Churyumov-Gerasimenko detected with the OSIRIS cameras on board Rosetta. Mon. Not. R. Astron. Soc. **462**, S57–S66 (2016)
K.-H. Glassmeier, H. Boehnhardt, D. Koschny, E. Kührt, I. Richter, The Rosetta mission: Flying towards the origin of the solar system. Space Sci. Rev. **128**, 1–21 (2007)
F. Goesmann, H. Rosenbauer, R. Roll, C. Szopa, F. Raulin, R. Sternberg, G. Israel, U. Meierhenrich, W. Thiemann, G. Munoz-Caro, Cosac, the cometary sampling and composition experiment on Philae. Space Sci. Rev. **128**, 257 (2007)
F. Goesmann, F. Raulin, J.H. Bredehöft, M. Cabane, P. Ehrenfreund, A.J. MacDermott, S. McKenna-Lawlor, U.J. Meierhenrich, G.M. Munoz Caro, C. Szopa, R. Sternberg, R. Roll, W.H.-P. Thiemann, S. Ulamec, COSAC prepares for sampling and in situ analysis of cometary matter from comet 67P/Churyumov-Gerasimenko. Planet. Space Sci. **103**, 318–330 (2014)
F. Goesmann, H. Rosenbauer, J.H. Bredehöft, M. Cabane, P. Ehrenfreund, T. Gautier, C. Giri, H. Krüger, L. Le Roy, A.J. MacDermott, S. McKenna-Lawlor, U.J. Meierhenrich, G.M.M. Caro, F. Raulin, R. Roll, A. Steele, H. Steininger, R. Sternberg, C. Szopa, W. Thiemann, S. Ulamec, Organic compounds on comet 67P/Churyumov-Gerasimenko revealed by COSAC mass spectrometry. Science **349**, aab0689 (2015)
O. Groussin, J.M. Sunshine, L.M. Feaga, L. Jorda, P.C. Thomas, J.-Y. Li, M.F. A'Hearn, M.J.S. Belton, S. Besse, B. Carcich, T.L. Farnham, D. Hampton, K. Klaasen, C. Lisse, F. Merlin, S. Protopapa, The temperature, thermal inertia, roughness and color of the nuclei of Comets 103P/Hartley 2 and 9P/Tempel 1. Icarus **222**, 580–594 (2013)
O. Groussin, N. Attree, Y. Brouet, V. Ciarletti, B. Davidsson, G. Filacchione, H.-H. Fischer, B. Gundlach, M. Knapmeyer, J. Knollenberg, R. Kokotanekova, E. Kührt, C. Leyrat, D. Marshall, I. Pelivan, Y. Skorov, C. Snodgrass, T. Spohn, F. Tosi, The thermal, mechanical, structural, and dielectric properties of cometary nuclei after Rosetta. Space Sci. Rev. **215**, 29 (2019)
S. Gulkis, M. Frerking, J. Crovisier, G. Beaudin, P. Hartogh, P. Encrenaz, T. Koch, C. Kahn, Y. Salinas, R. Nowicki, R. Irigoyen, M. Janssen, P. Stek, M. Hofstadter, M. Allen, C. Backus, L. Kamp, C. Jarchow, E. Steinmetz, A. Deschamps, J. Krieg, M. Gheudin, D. Bockelee-Morvan, N. Biver, T. Encrenaz, D. Despois, W. Ip, E. Lellouch, I. Mann, D. Muhleman, H. Rauer, P. Schloerb, T. Spilker, MIRO: Microwave instrument for Rosetta orbiter. Space Sci. Rev. **128**, 561–597 (2007)

S. Gulkis, M. Allen, P. von Allmen, G. Beaudin, N. Biver, D. Bockelee-Morvan, M. Choukroun, J. Crovisier, B.J.R. Davidsson, P. Encrenaz, T. Encrenaz, M. Frerking, P. Hartogh, M. Hofstadter, W.-H. Ip, M. Janssen, C. Jarchow, S. Keihm, S. Lee, E. Lellouch, C. Leyrat, L. Rezac, F.P. Schloerb, T. Spilker, Subsurface properties and early activity of comet 67P/Churyumov-Gerasimenko. Science **347**, aaa0709 (2015)

B. Gundlach, J. Blum, Outgassing of icy bodies in the Solar System—II: Heat transport in dry, porous surface dust layers. Icarus **219**, 618 (2012)

B. Gundlach, S. Kilias, E. Beitz, J. Blum, Micrometer-sized ice particles for planetary-science experiments—I. Preparation, critical rolling friction force, and specific surface energy. Icarus **214**, 717–723 (2011)

B. Gundlach, K.P. Schmidt, C. Kreuzig, D. Bischoff, F. Rezaei, S. Kothe, J. Blum, B. Grzesik, E. Stoll, The tensile strength of ice and dust aggregates and its dependence on particle properties. Mon. Not. R. Astron. Soc. **479**, 1273–1277 (2018)

P.J. Gutierrez et al., Possible interpretation of the precession of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **590**, A46 (2016)

E. Hand, NASA set to choose low-cost Solar System mission. Nature **487**, 151 (2012)

W.M. Harris, M.R. Combi, R.K. Honeycutt, B.E.A. Mueller, F. Scherb, Evidence for interacting gas flows and an extended volatile source distribution in the coma of Comet C/1996 B2 (Hyakutake). Science **277**, 676 (1997)

P. Hartogh, D.C. Lis, D. Bockelee-Morvan, M. de Val-Borro, N. Biver, M. Küppers, M. Emprechtinger, E.A. Bergin, J. Crovisier, M. Rengel, R. Moreno, S. Szutowicz, G.A. Blake, Ocean-like water in the Jupiter-family comet 103P/Hartley 2. Nature **478**, 218–220 (2011)

M. Hässig, K. Altwegg, H. Balsiger, A. Bar-Nun, J.J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S.A. Fuselier, M. Galand, S. Gasc, T.I. Gombosi, K.C. Hansen, A. Jäckel, H.U. Keller, E. Kopp, A. Korth, E. Kührt, L. Le Roy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Rème, M. Rubin, T. Sémon, C. Tornow, C.-Y. Tzou, J.H. Waite, P. Wurz, Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko. Science **347**, aaa0276 (2015)

M. Hässig, K. Altwegg, H. Balsiger, J.J. Berthelier, A. Bieler, U. Calmonte, F. Dhooghe, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, L. Le Roy, A. Luspay-Kuti, K. Mandt, M. Rubin, C.-Y. Tzou, S.F. Wampfler, P. Wurz, Isotopic composition of CO_2 in the coma of 67P/Churyumov-Gerasimenko measured with ROSINA/DFMS. Astron. Astrophys. **605**, A50 (2017)

A. Herique, W. Kofman, P. Beck, L. Bonal, I. Buttarazzi, E. Heggy, J. Lasue, A.C. Levasseur-Regourd, E. Quirico, S. Zine, Cosmochemical implications of CONSERT permittivity characterization of 67P/CG. Mon. Not. R. Astron. Soc. **462**, S516–S532 (2016)

A. Herique et al., Direct observations of asteroid interior and regolith structure: science measurement requirements. Adv. Space Res. **62**, 2141–2162 (2018)

B. Hermalyn, T.L. Farnham, S.M. Collins, M.S. Kelley, M.F. A'Hearn, D. Bodewits, B. Carcich, D.J. Lindler, C. Lisse, K. Meech, P.H. Schultz, P.C. Thomas, The detection, localization, and dynamics of large icy particles surrounding Comet 103P/Hartley 2. Icarus **222**, 625–633 (2013)

T. Hewagama, S. Aslam, P. Clark, M. Daly, L. Feaga, D. Folta, N. Gorius, T. Hurford, T.A. Livengood, B. Malphrus, M. Mumma, C. Nixon, J. Sunshine, G. Villanueva, A. Zucherman, Primitive Object Volatile Explorer (PrOVE)—Waypoints and opportunistic deep space missions to comets, in *Lunar and Planetary Science Conference, 49* (2018), p. 2800

M. Hilchenbach, J. Kissel, Y. Langevin, C. Briois, H. von Hoerner, A. Koch, R. Schulz, J. Silén, K. Altwegg, L. Colangeli, H. Cottin, C. Engrand, H. Fischer, A. Glasmachers, E. Grün, G. Haerendel, H. Henkel, H. Höfner, K. Hornung, E.K. Jessberger, H. Lehto, K. Lehto, F. Raulin, L. Le Roy, J. Rynö, W. Steiger, T. Stephan, L. Thirkell, R. Thomas, K. Torkar, K. Varmuza, K.-P. Wanczek, N. Altobelli, D. Baklouti, A. Bardyn, N. Fray, H. Krüger, N. Ligier, Z. Lin, P. Martin, S. Merouane, F.R. Orthous-Daunay, J. Paquette, C. Revillet, S. Siljeström, O. Stenzel, B. Zaprudin, Comet 67P/Churyumov-Gerasimenko: Close-up on dust particle fragments. Astrophys. J. **816**, L32 (2016)

T.-M. Ho, V. Baturkin, C. Grimm, J.T. Grundmann, C. Hobbie, E. Ksenik, C. Lange, K. Sasaki, M. Schlotterer, M. Talapina, N. Termtanasombat, E. Wejmo, L. Witte, M. Wrasmann, G. Wübbels, J. Rössler, C. Ziach, R. Findlay, J. Biele, C. Krause, S. Ulamec, M. Lange, O. Mierheim, R. Lichtenheldt, M. Maier, J. Reill, H.-J. Sedlmayr, P. Bousquet, A. Bellion, O. Bompis, C. Cenac-Morthe, M. Deleuze, S. Fredon, E. Jurado, E. Canalias, R. Jaumann, J.-P. Bibring, K.H. Glassmeier, D. Hercik, M. Grott, L. Celotti, F. Cordero, J. Hendrikse, T. Okada, MASCOT—The mobile asteroid surface scout onboard the Hayabusa2 mission. Space Sci. Rev. **208**, 339–374 (2017)

S. Ivanovski, V. Zakharov, V. Della Corte, F. Lucarelli, J.-F. Crifo, A. Rotundi, M. Fulle, Aspherical dust dynamics code for GIADA experiment in the coma of 67P/Churyumov-Gerasimenko, in *Proceedings EGU General Assembly Conference Abstracts, 16*, 15664 (2014)

D. Jewitt, H.H. Hsieh, J. Agarwal, in *Asteroids III*, ed. by P. Michel, F. Demeo, W. Bottke (University of Arizona Press, Tucson, 2015), p. 221

G.H. Jones, J. Agarwal, N. Bowles, M. Burchell, A.J. Coates, A. Fitzsimmons, A. Graps, H.H. Hsieh, C.M. Lisse, S.C. Lowry, A. Masters, C. Snodgrass, C. Tubiana, The proposed Caroline ESA M3 mission to a Main Belt Comet. Adv. Space Res. **62**, 1921–1946 (2018)

S. Keihm, F. Tosi, L. Kamp, F. Capaccioni, S. Gulkis, D. Grassi, M. Hofstadter, G. Filacchione, S. Lee, S. Giuppi, M. Janssen, M. Capria, Interpretation of combined infrared, submillimeter, and millimeter thermal flux data obtained during the Rosetta fly-by of Asteroid (21) Lutetia. Icarus **221**, 395–404 (2012)

H.U. Keller, The nucleus, in *Physics and Chemistry of Comets*, ed. by W.F. Huebner (Springer, Berlin, 1990)

H.U. Keller, S. Mottola, S.F. Hviid, J. Agarwal, E. Kührt, Y. Skorov, K. Otto, J.-B. Vincent, N. Oklay, S.E. Schröder, B. Davidsson, M. Pajola, X. Shi, D. Bodewits, I. Toth, F. Preusker, F. Scholten, H. Sierks, C. Barbieri, P. Lamy, R. Rodrigo, D. Koschny, H. Rickman, M.F. A'Hearn, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, J. Deller, S. Fornasier, M. Fulle, O. Groussin, P.J. Gutierrez, C. Güttler, M. Hofmann, W.-H. Ip, L. Jorda, J. Knollenberg, J.R. Kramm, M. Küppers, L.-M. Lara, M. Lazzarin, J.J. Lopez-Moreno, F. Marzari, G. Naletto, C. Tubiana, N. Thomas, Seasonal mass transfer on the nucleus of comet 67P/Chuyumov-Gerasimenko. Mon. Not. R. Astron. Soc. **469**, S357–S371 (2017)

M.S.P. Kelley, C.E. Woodward, D. Bodewits, T.L. Farnham, M.S. Gudipati, D.E. Harker, D.C. Hines, M.M. Knight, L. Kolokolova, A. Li, I. de Pater, S. Protopapa, R.W. Russell, M.L. Sitko, D.H. Wooden, Cometary science with the James Webb Space Telescope. Publ. Astron. Soc. Pac. **128**, 018009 (2016)

G. Klingelhöfer, J. Brückner, C. D'uston et al., The Rosetta alpha particle X-ray spectrometer (APXS). Space Sci. Rev. **128**, 383–396 (2007)

H.W. Kochan, W.F. Huebner, D.W.G. Sears, Simulation experiments with cometary analogous material. Earth Moon Planets **80**, 369–411 (1998)

W. Kofman, Y. Barbin, J. Klinger, A.-C. Levasseur-Regourd, J.-P. Barriot, A. Herique, T. Hagfors, E. Nielsen, E. Grün, P. Edenhofer, H. Kochan, G. Picardi, R. Seu, J. van Zyl, C. Elachi, J. Melosh, J. Veverka, P. Weissman, L.H. Svedhem, S.E. Hamran, I.P. Williams, Comet nucleus sounding experiment by radiowave transmission. Adv. Space Res. **21**, 1589–1598 (1998)

W. Kofman, A. Herique, J.-P. Goutail, T. Hagfors, I.P. Williams, E. Nielsen, J.-P. Barriot, Y. Barbin, C. Elachi, P. Edenhofer, A.-C. Levasseur-Regourd, D. Plettemeier, G. Picardi, R. Seu, V. Svedhem, The comet nucleus sounding experiment by radiowave transmission (CONSERT): A short description of the instrument and of the commissioning stages. Space Sci. Rev. **128**, 413–432 (2007)

W. Kofman, A. Herique, Y. Barbin, J.-P. Barriot, V. Ciarletti, S. Clifford, P. Edenhofer, C. Elachi, C. Eyraud, J.-P. Goutail, E. Heggy, L. Jorda, J. Lasue, A.-C. Levasseur-Regourd, E. Nielsen, P. Pasquero, F. Preusker, P. Puget, D. Plettemeier, Y. Rogez, H. Sierks, C. Statz, H. Svedhem, I. Williams, S. Zine, J. Van Zyl, Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar. Science **349**, aab0639 (2015)

R. Kokotanekova, C. Snodgrass, P. Lacerda, S.F. Green, S.C. Lowry, Y.R. Fernandez, C. Tubiana, A. Fitzsimmons, H.H. Hsieh, Rotation of cometary nuclei: New light curves and an update of the ensemble properties of Jupiter-family comets. Mon. Not. R. Astron. Soc. **471**, 2974–3007 (2017)

R. Kokotanekova, C. Snodgrass, P. Lacerda, S.F. Green, P. Nikolov, T. Bonev, Implications of the small spin changes measured for large Jupiter-family comet nuclei. Mon. Not. R. Astron. Soc. **479**, 4665–4680 (2018)

P.L. Lamy, I. Toth, B.J.R. Davidsson, O. Groussin, P. Gutierrez, L. Jorda, M. Kaasalainen, S.C. Lowry, A portrait of the nucleus of Comet 67P/Churyumov-Gerasimenko. Space Sci. Rev. **128**, 23–66 (2007)

L. Le Roy, K. Altwegg, H. Balsiger, J.-J. Berthelier, A. Bieler, C. Briois, U. Calmonte, M.R. Combi, J. De Keyser, F. Dhooghe, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, M. Hässig, A. Jäckel, M. Rubin, C.-Y. Tzou, Inventory of the volatiles on comet 67P/Churyumov-Gerasimenko from Rosetta/ROSINA. Astron. Astrophys. **583**, A1 (2015)

A. Lethuillier, A. Le Gall, M. Hamelin, W. Schmidt, K.J. Seidensticker, R. Grard, V. Ciarletti, S. Caujolle-Bert, H.-H. Fischer, R. Trautner, Electrical properties and porosity of the first meter of the nucleus of 67P/Churyumov-Gerasimenko. As constrained by the Permittivity Probe SESAME-PP/Philae/Rosetta. Astron. Astrophys. **591**, A32 (2016)

H.F. Levison, in *Completing the Inventory of the Solar System*, ed. by T. Rettig, J.M. Hahn. Astronomical Society of the Pacific Conference Series, vol. 107, San Francisco (1996), p. 173

Y. Liao, Global explorations of inner neutral gas coma of Comet 67P/Churyumov-Gerasimenko with DSMC approach. Ph.D. thesis, University of Bern (2017)

D.J. Lien, Dust in comets. I. Thermal properties of homogeneous and heterogeneous grains. Astrophys. J. **355**, 680 (1990)

Z.-Y. Lin, W.-H. Ip, I.-L. Lai, J.-C. Lee, J.-B. Vincent, L.M. Lara, D. Bodewits, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.F. A'Hearn, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, S. Fornasier, M. Fulle, O. Groussin, P.J. Gutièrrez, C.G. üttler, S.F. Hviid, L. Jorda, J. Knollenberg, G. Kovacs, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, M. Lazzarin, J.J. Lopez-Moreno, S. Lowry, F. Marzari, H. Michalik, S. Mottola, G. Naletto, N. Oklay, M. Pajola, A. Rozek, N. Thomas, Y. Liao, C. Tubiana, Morphology and dynamics of the jets of comet 67P/Churyumov-Gerasimenko: early-phase development. Astron. Astrophys. **583**, A11 (2015)

D.C. Lis, D. Bockelée-Morvan, R. Güsten, N. Biver, J. Stutzki, Y. Delorme, C. Duràn, H. Wiesemeyer, Y. Okada, Terrestrial deuterium-to-hydrogen ratio in water in hyperactive comets. Astron. Astrophys. **625**, L5 (2019)

S. Lorek, B. Gundlach, P. Lacerda, J. Blum, Comet formation in collapsing pebble clouds. What cometary bulk density implies for the cloud mass and dust-to-ice ratio. Astron. Astrophys. **587**, A128 (2016)

S. Lowry, S.R. Duddy, B. Rozitis, S.F. Green, A. Fitzsimmons, C. Snodgrass, H.H. Hsieh, O. Hainaut, The nucleus of Comet 67P/Churyumov-Gerasimenko. A new shape model and thermophysical analysis. Astron. Astrophys. **548**, L12 (2012)

LSST Science Collaboration, LSST Science Book (2009). arXiv:0912.0201

U. Marboeuf, B. Schmitt, J.-M. Petit, O. Mousis, N. Fray, A cometary nucleus model taking into account all phase changes of water ice: Amorphous, crystalline, and clathrate. Astron. Astrophys. **542**, A82 (2012)

R.M. Marschall, L. Rezac, D. Kappel, C.C. Su, S.-B. Gerig, M. Rubin, O. Pinzon-Rodriguez, D. Marshall, Y. Liao, C. Herny, G. Arnold, C. Christou, S.K. Dadzie, O. Groussin, P. Hartogh, L. Jorda, E. Kührt, S. Mottola, O. Mousis, F. Preusker, F. Scholten, P. Theologou, J.-S. Wu, K. Altwegg, R. Rodrigo, N. Thomas, A comparison of multiple Rosetta data sets and 3D model calculations of 67P/Churyumov-Gerasimenko coma around equinox. Icarus **328**, 104 (2019)

B. Marty, K. Altwegg, H. Balsiger, A. Bar-Nun, D.V. Bekaert, J.-J. Berthelier, A. Bieler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, K.C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, O. Mousis, T. Owen, H. Rème, M. Rubin, T. Sèmon, C.-Y. Tzou, J.H. Waite, P. Wurz, Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth's atmosphere. Science **356**, 1069–1072 (2017)

M. Massironi et al., Two independent and primitive envelopes of the bilobate nucleus of comet 67P. Nature **526**, 402–405 (2015)

J.A.M. McDonnell, P.L. Lamy, G.S. Pankiewicz, Physical properties of cometary dust, in *IAU Colloq. 116: Comets in the Post-Halley Era*, vol. 167 (1991), pp. 1043–1073

K.J. Meech, J.C. Castillo-Rogez, in *IAU General Assembly*, vol. 22 (2015), 2257859

K.J. Meech et al., EPOXI: Comet 103P/Hartley 2 observations from a worldwide campaign. Astrophys. J. **734**, L1 (2011)

S. Merouane, B. Zaprudin, O. Stenzel, Y. Langevin, N. Altobelli, V. Della Corte, H. Fischer, M. Fulle, K. Hornung, J. Silén, N. Ligier, A. Rotundi, J. Ryno, R. Schulz, M. Hilchenbach, J. Kissel (Cosima Team), Dust particle flux and size distribution in the coma of 67P/Churyumov-Gerasimenko measured in situ by the COSIMA instrument on board Rosetta. Astron. Astrophys. **596**, A87 (2016)

P. Michel, M. Kueppers, H. Sierks, I. Carnelli, A.F. Cheng, K. Mellab, M. Granvik, A. Kestilä, T. Kohout, K. Muinonen, A. Näsilä, A. Penttila, T. Tikka, P. Tortora, V. Ciarletti, A. Hérique, N. Murdoch, E. Asphaug, A. Rivkin, O. Barnouin, A.C. Bagatin, P. Pravec, D.C. Richardson, S.R. Schwartz, K. Tsiganis, S. Ulamec, O. Karatekin, European component of the AIDA mission to a binary asteroid: characterization and interpretation of the impact of the DART mission. Adv. Space Res. **62**, 2261 (2018)

A. Migliorini, G. Piccioni, F. Capaccioni, G. Filacchione, D. Bockelée-Morvan, S. Erard, C. Leyrat, M.R. Combi, N. Fougere, J. Crovisier, F.W. Taylor, M.C. De Sanctis, M.T. Capria, D. Grassi, G. Rinaldi, G.P. Tozzi, U. Fink, Water and carbon dioxide distribution in the 67P/Churyumov-Gerasimenko coma from VIRTIS-M infrared observations. Astron. Astrophys. **589**, A45 (2016)

D. Möhlmann, Surface regolith and environment of comets. Planet. Space Sci. **42**, 933–937 (1994)

A. Morse, D. Andrews, G. Morgan et al., Ptolemy operations at the surface of a comet, from planning to reality. Acta Astron. **125**, 196–211 (2016)

S. Mottola, G. Arnold, H.-G. Grothues et al., The structure of the regolith on 67P/Churyumov-Gerasimenko from ROLIS descent imaging. Science **349**, aab0232 (2015)

Mottola (2019, in preparation)

D. Nesvorny, D. Vokrouhlicky, L. Dones, H.F. Levison, N. Kaib, A. Morbidelli, Origin and evolution of short-period comets. Astrophys. J. **845**, 27 (2017)

M. Neugebauer, G. Gloeckler, J.T. Gosling, A. Rees, R. Skoug, B.E. Goldstein, T.P. Armstrong, M.R. Combi, T. Mäkinen, D.J. McComas, R. von Steiger, T.H. Zurbuchen, E.J. Smith, J. Geiss, L.J. Lanzerotti, Encounter of the Ulysses spacecraft with the ion tail of Comet McNaught. Astrophys. J. **667**, 1262 (2007)

T. Ott et al., Dust mass distribution around comet 67P/Churyumov-Gerasimenko determined via parallax measurements using Rosetta's OSIRIS cameras. Mon. Not. R. Astron. Soc. **469**, S276–S284 (2017)

M. Pajola et al., The pristine interior of comet 67P revealed by the combined Aswan outburst and cliff collapse. Nat. Astron. **1**, 0092 (2017)

M. Pätzold et al., in *AAS/Division for Planetary Sciences Meeting Abstracts, 48*, 116.27 (2016)

M. Pätzold, T.P. Andert, M. Hahn, J.-P. Barriot, S.W. Asmar, B. Häusler, M.K. Bird, S. Tellmann, J. Oschlisniok, K. Peter, The nucleus of comet 67P/Churyumov-Gerasimenko—Part I: The global view—Nucleus mass, mass-loss, porosity, and implications. Mon. Not. R. Astron. Soc. **483**, 2337–2346 (2019)

A. Pommerol, B. Jost, O. Poch, M.R. El-Maarry, B. Vuitel, N. Thomas, The SCITEAS experiment: Optical characterizations of sublimating icy planetary analogues. Planet. Space Sci. **109**, 106–122 (2015a)

A. Pommerol, N. Thomas, M.R. El-Maarry, M. Pajola, O. Groussin, A.-T. Auger, N. Oklay, S. Fornasier, C. Feller, B. Davidsson, A. Gracia, B. Jost, R. Marschall, O. Poch, M.A. Barucci, J.-L. Bertaux, F. La Forgia, H.U. Keller, E. Kuehrt, S.C. Lowry, S. Mottola, G. Naletto, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, H. Rickman, D. Koschny, J. Agarwal, M.F. A'Hearn, I. Bertini, G. Cremonese, V. Da Deppo, M. De Cecco, S. Debei, C. Guettler, M. Fulle, P.J. Gutierrez, S.F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, G. Kovacs, J.-R. Kramm, M. Küppers, L. Lara, M. Lazzarin, J.L. Lopez Moreno, F. Marzari, H. Michalik, F. Preusker, F. Scholten, C. Tubiana, J.-B. Vincent, OSIRIS observations of metre-size exposures of H_2O ice at the surface of 67P/Churyumov-Gerasimenko and interpretation using laboratory experiments. Astron. Astrophys. **583**, A25 (2015b). https://doi.org/10.1051/0004-6361/201525977

F. Preusker, F. Scholten, K.-D. Matz, T. Roatsch, S.F. Hviid, S. Mottola, J. Knollenberg, E. Kührt, M. Pajola, N. Oklay, J.-B. Vincent, B. Davidsson, M.F. A'Hearn, J. Agarwal, C. Barbieri, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, S. Fornasier, M. Fulle, O. Groussin, P.J. Gutièrrez, C. Güttler, W.-H. Ip, L. Jorda, H.U. Keller, D. Koschny, J.R. Kramm, M. Küppers, P. Lamy, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, M. Massironi, G. Naletto, H. Rickman, R. Rodrigo, H. Sierks, N. Thomas, C. Tubiana, The global meter-level shape model of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **607**, L1 (2017)

A. Rivkin, B.A. Cohen, O.S. Barnouin, N.L. Chabot, C.M. Ernst, R.L. Klima, J. Helbert, Z. Sternovsky, The Main-belt Asteroid and NEO Tour with Imaging and Spectroscopy (MANTIS), AGU Fall Meeting Abstracts, P11B-2087 (2015)

F. Robert, in *Meteorites and the Early Solar System II*, ed. by D.S. Lauretta, H.Y. McSween (2006), p. 341

RoLand, Cometary Lander for the Rosetta Mission. Proposal to ESA (1995)

R. Schräpler, J. Blum, I. von Borstel, C. Güttler, The stratification of regolith on celestial objects. Icarus **257**, 33 (2015)

S.E. Schröder, S. Mottola, G. Arnold et al., Close-up images of the final Philae landing site on comet 67P/Churyumov-Gerasimenko acquired by the ROLIS camera. Icarus **285**, 263–274 (2016)

K.J. Seidensticker, D. Möhlmann, I. Apathy, W. Schmidt, K. Thiel, W. Arnold, H.-H. Fischer, M. Kretschmer, D. Madlener, A. Peter, R. Trautner, S. Schieke, Sesame—An experiment of the Rosetta Lander Philae: Objectives and general design. Space Sci. Rev. **128**, 301–337 (2007)

X. Shi, X. Hu, S. Mottola, M. Rose, H. Sierks, C. Güttler, H.U. Keller, Observing and modeling the near-nucleus coma structure around terminators on 67P/Churyumov-Gerasimenko, in *European Planetary Science Congress, 11*, EPSC2017-487 (2017)

C. Snodgrass et al., The 67P/Churyumov-Gerasimenko observation campaign in support of the Rosetta mission. Philos. Trans. R. Soc. Lond. Ser. A **375**, 20160249 (2017a)

C. Snodgrass, J. Agarwal, M. Combi, A. Fitzsimmons, A. Guilbert-Lepoutre, H.H. Hsieh, M.-T. Hui, E. Jehin, M.S.P. Kelley, M.M. Knight, C. Opitom, R. Orosei, M. de Val-Borro, B. Yang, The main belt comets and ice in the solar system. Astron. Astrophys. Rev. **25**, 5 (2017b)

C. Snodgrass, G.H. Jones, H. Boehnhardt, A. Gibbings, M. Homeister, N. Andre, P. Beck, M.S. Bentley, I. Bertini, N. Bowles, M.T. Capria, C. Carr, M. Ceriotti, A.J. Coates, V. Della Corte, K.L. Donaldson Hanna, A. Fitzsimmons, P.J. Gutiérrez, O.R. Hainaut, A. Herique, M. Hilchenbach, H.H. Hsieh, E. Jehin, O. Karatekin, W. Kofman, L.M. Lara, K. Laudan, J. Licandro, S.C. Lowry, F. Marzari, A. Masters, K.J. Meech, F. Moreno, A. Morse, R. Orosei, A. Pack, D. Plettemeier, D. Prialnik, A. Rotundi, M. Rubin, J.P. Sanchez, S. Sheridan, M. Trieloff, A. Winterboer, The Castalia mission to Main Belt Comet 133P/Elst-Pizarro. Adv. Space Res. **62**, 1947–1976 (2018)

T. Spohn, K. Seiferlin, A. Hagermann, J. Knollenberg, A.J. Ball, M. Banaszkiewicz, J. Benkhoff, S. Gadomski, W. Gregorczyk, J. Grygorczuk, M. Hlond, G. Kargl, E. Kührt, N. Kömle, J. Krasowski, W. Marczewski, J.C. Zarnecki, Mupus—a thermal and mechanical properties probe for the Rosetta lander Philae. Space Sci. Rev. **128**, 339 (2007)

T. Spohn, J. Knollenberg, A.J. Ball, M. Banaszkiewicz, J. Benkhoff, M. Grott, J. Grygorczuk, C. Hüttig, A. Hagermann, G. Kargl, E. Kaufmann, N. Kömle, E. Kührt, K.J. Kossacki, W. Marczewski, I. Pelivan, R. Schrödter, K. Seiferlin, Thermal and mechanical properties of the near-surface layers of comet 67P/Churyumov-Gerasimenko. Science **349**, aab0464 (2015)

S.A. Stern et al., Initial results from the New Horizons exploration of 2014 MU_{69}, a small Kuiper Belt object. Science **364**, aaw9771 (2019)

J. Sunshine, N. Thomas, M.R. El Maarry, T. Farnham, J. Geophys. Res., Planets **121**, 2194–2210 (2016)

V. Tenishev, N. Fougere, D. Borovikov, M.R. Combi, A. Bieler, K.C. Hansen, T.I. Gombosi, A. Migliorini, F. Capaccioni, G. Rinaldi, G. Filacchione, L. Kolokolova, U. Fink, Analysis of the dust jet imaged by Rosetta VIRTIS-M in the coma of comet 67P/Churyumov-Gerasimenko on 2015 April 12. Mon. Not. R. Astron. Soc. **462**, S370 (2016)

N. Thomas, B. Davidsson, M.R. El-Maarry, S. Fornasier, L. Giacomini, A.G. Gracia Berna, S.F. Hviid, W.-H. Ip, L. Jorda, H.U. Keller, J. Knollenberg, E. Kührt, F. La Forgia, I.L. Lai, Y. Liao, R. Marschall, M. Massironi, S. Mottola, M. Pajola, O. Poch, A. Pommerol, F. Preusker, F. Scholten, C.C. Su, J.S. Wu, J.-B. Vincent, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, H. Rickman, D. Koschny, M.F. A'Hearn, M.A. Barucci, J-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. Fulle, O. Groussin, P.J. Gutierrez, J.-R. Kramm, M. Küppers, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, H. Michalik, G. Naletto, C. Güttler, Redistribution of particles across the nucleus of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **583**, A17 (2015a). https://doi.org/10.1051/0004-6361/201526049

N. Thomas, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, H. Rickman, D. Koschny, H.U. Keller, J. Agarwal, M.F. A'Hearn, F. Angrilli, A.-T. Auger, M.A. Barucci, J.-L. Bertaux, I. Bertini, S. Besse, D. Bodewits, G. Cremonese, V. Da Deppo, B. Davidsson, M. De Cecco, S. Debei, M.-R. El-Maarry, F. Ferri, S. Fornasier, M. Fulle, L. Giacomini, O. Groussin, P.J. Gutierrez, C. Güttler, S.F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, S. Magrin, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, A. Pommerol, F. Preusker, L. Sabau, F. Scholten, C. Snodgrass, C. Tubiana, J.-B. Vincent, K.-P. Wenzel, The morphological diversity of Comet 67P/Churyumov-Gerasimenko. Science **347**, aaa0440 (2015b)

N. Thomas, M.R. El Maarry, P. Theologou, F. Preusker, F. Scholten, L. Jorda, S.F. Hviid, R. Marschall, E. Kührt, G. Naletto, H. Sierks, P.L. Lamy, R. Rodrigo, D. Koschny, B. Davidsson, M.A. Barucci, J.L. Bertaux, I. Bertini, D. Bodewits, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, S. Fornasier, M. Fulle, O. Groussin, P.J. Gutierrez, C. Güttler, W.H. Ip, H.U. Keller, J. Knollenberg, L.M. Lara, M. Lazzarin, J.J. Lopez-Moreno, F. Marzari, C. Tubiana, J.B. Vincent, Regional unit definition for the nucleus of comet 67P/Churyumov-Gerasimenko on the SHAP7 model. Planet. Space Sci. **164**, 19–36 (2018)

C.-Y. Tzou Ph.D. thesis, Univ. Bern (2017)

S. Ulamec, J. Block, M. Fenzi et al., RoLand, a long term Lander for the Rosetta Mission. Space Technol. **17**(1), 59–64 (1997)

S. Ulamec, V. Kucherenko, J. Biele, A. Bogatchev, A. Makurin, S. Matrossov, Hopper concepts for small body landers. Adv. Space Res. **47**, 428–439 (2011)

S. Ulamec, C. Fantinati, M. Maibaum, K. Geurts, J. Biele, S. Jansen, O. Küchemann, B. Cozzoni, F. Finke, V. Lommatsch, A. Moussi-Soffys, C. Delmas, L. O'Rourke, Rosetta Lander—Landing and operations on comet 67P/Churyumov-Gerasimenko. Acta Astronaut. **125**, 80–91 (2016)

S. Ulamec, L. O'Rourke, J. Biele, B. Grieger, R. Andrés, S. Lodiot, P. Munoz, A. Charpentier, S. Mottola, J. Knollenberg, M. Knapmeyer, E. Kührt, F. Scholten, K. Geurts, M. Maibaum, C. Fantinati, O. Küchemann, V. Lommatsch, C. Delmas, E. Jurado, R. Garmier, T. Martin, Rosetta Lander—Philae: Operations on comet 67P/Churyumov-Gerasimenko, analysis of wake-up activities and final state. Acta Astronaut. **137**, 38–43 (2017)

J.-B. Vincent et al., Constraints on cometary surface evolution derived from a statistical analysis of 67P's topography. Mon. Not. R. Astron. Soc. **469**, S329–S338 (2017)

K. Wittmann, B. Feuerbacher, S. Ulamec, H. Rosenbauer, J.P. Bibring, D. Moura et al., Rosetta Lander in situ characterization of a comet nucleus. Acta Astronaut. **45**, 389 (1999)

I.P. Wright, S. Barber, G. Morgan et al., Ptolemy—An instrument to measure stable isotopic ratios of key volatiles on a cometary nucleus. Space Sci. Rev. **128**, 363–381 (2007)

I.P. Wright, S. Sheridan, S.J. Barber, G.H. Morgan, D.J. Andrews, A.D. Morse, CHO-bearing organic compounds at the surface of 67P/Churyumov-Gerasimenko revealed by Ptolemy. Science **349**, aab0673 (2015)

V.V. Zakharov, S.L. Ivanovski, J.-F. Crifo, V. Della Corte, A. Rotundi, M. Fulle, Asymptotics for spherical particle motion in a spherically expanding flow. Icarus **312**, 121–127 (2018)

H. Zhang, B.C. Li, J.J. Yin, W.G. Wang, J.C. Huang, C.-H. Hsia, Scientific objectives and design concept of the spectrometers for proposed flyby mission to Main Belt Comet 133p/Elst-Pizarro, in *50th Lunar and Planetary Science Conference*, 2462 (2019)